

Injection of coal and waste plastics in blast furnaces

Anne M Carpenter

CCC/166

March 2010

Copyright © IEA Clean Coal Centre

ISBN 978-92-9029-486-3

Abstract

The majority of waste plastics currently produced are either landfilled or incinerated. Plastics do not readily degrade and toxic elements can be leached from the landfill. Combustion of waste plastics can generate environmentally hazardous air pollutants such as dioxins/furans, as well as undesirable carbon dioxide. Consequently, cost effective ways of recycling the increasing amounts of generated waste plastics are required, preferably by turning them into marketable commodities. One way of achieving this is by injecting them with coal into blast furnaces (BFs). A factor restricting the utilisation of waste plastics is the cost of their collection and treatment. The majority of waste plastics that are injected originate from packaging and container wastes. The wastes are highly heterogeneous, consisting of different types of plastics, as well as contaminants. Chlorine content is of concern due to its corrosive effects and consequently needs to be removed from the waste plastics. Blending can optimise the relative strengths of the constituent coals, diluting unfavourable properties, and reduce raw material costs since cheaper coals can be incorporated. The quality of the coal blend and waste plastic feed should be consistent to ensure stable BF operation. How the composition and properties of the injectants (and the iron ore and coke) influence the operation, stability and productivity of a BF, the quality of the hot metal product, and the offgas composition are discussed. The combustibility of the injectants is particularly important because of the affect on furnace permeability. Utilising injectants with a high burnout and optimising operating conditions, such as blast temperature and oxygen enrichment, can improve combustion efficiency. Interactions between coal and wastes plastics can be exploited to improve their combustion efficiency. It is concluded that coal and waste plastics injection can help BF operators maximise productivity, whilst reducing costs and minimising environmental impacts.

Acronyms and abbreviations

ad	air dried
ASR	automotive shredder residue
BF	blast furnace
CV	calorific value
db	dry basis
DTF	drop tube furnace
ELV	end-of-life vehicles
EPS	expanded polystyrene
EU	European Union
GCI	granular coal injection
HDPE	high density polyethylene
IDT	initial deformation temperature
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LDPE	low density polyethylene
LV	low volatile
HT	hemispherical temperature
HV	high volatile
MV	mid volatile
MSW	municipal solid wastes
Mt	million tonnes
PBT	polybutylene terephthalate
PC	pulverised coal
PCI	pulverised coal injection
PE	polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PS	polystyrene
PVC	polyvinylchloride
RR	replacement ratio
ST	softening temperature
TGA	thermal gravimetric analysis
thm	tonne of hot metal
VM	volatile matter
WEEE	waste electrical and electronic equipment
WMR	wire mesh reactor
WPI	waste plastics injection

Contents

Acronyms and abbreviations	2
Contents	3
1 Introduction	5
2 The blast furnace	7
2.1 Blast furnace process	7
2.2 Chemistry	8
2.3 Process issues	8
2.3.1 Iron ore	9
2.3.2 Coke	10
3 Quality of coal and waste plastics	11
3.1 Coal	11
3.1.1 Coal types and blends	11
3.1.2 Coal properties and evaluation	13
3.2 Waste plastics	15
3.2.1 Types of plastics	17
3.2.2 Properties	18
4 Preparation and injection	20
4.1 Coal preparation	20
4.1.1 Drying	21
4.1.2 Wear	21
4.1.3 Power consumption and capacity	21
4.1.4 Blends	21
4.2 Waste plastics preparation	22
4.3 Injection system	24
4.3.1 Injection vessels arrangement	24
4.3.2 Conveying line	25
4.3.3 Injection lances	26
5 Combustion	28
5.1 Combustion process	28
5.2 Effect of coal rank and plastic types	30
5.2.1 Coal	30
5.2.2 Waste plastics	31
5.3 Particle size effects	32
5.3.1 Coal	32
5.3.2 Waste plastics and co-injection with coal	33
5.3.3 Summary	37
5.4 Operational factors	37
5.4.1 Oxygen concentration	37
5.4.2 Blast temperature and moisture	38
6 Unburnt char	39
6.1 Char gasification	39
6.2 Interactions with liquid metal	40
6.3 Interactions with slag	41
6.4 Slag viscosity	41
7 Hot metal quality	42
7.1 Silicon	42
7.2 Sulphur	42
7.3 Trace metals	43

8	Environmental aspects	46
8.1	Offgas	46
8.2	Emissions	46
8.3	CO ₂ emissions and abatement	47
8.4	Waste water and by-products	49
9	Conclusions	51
10	References	53

I Introduction

Waste plastics are being produced in ever increasing quantities due to the growth in the use of plastic products. The majority of this material is currently being landfilled or incinerated. Unfortunately, the synthetic polymers in the plastics do not readily degrade and leaching of toxic elements from the landfill can occur. When combusted, waste plastics often generate environmentally hazardous pollutants, such as dioxins/furans, as well as environmentally undesirable carbon dioxide. Landfill costs are rising and in many places space is running out. Public opposition to additional waste disposal facilities is growing, especially in Western countries. With legislation limiting the amount of wastes that can be landfilled, such as the recent European Union (EU) Directive on waste management (Official Journal of the European Union, 2008), cost effective ways of dealing with the generated wastes are needed, preferably by turning them into marketable commodities.

There are various alternatives for recycling waste plastics. Mechanical (or materials) recycling is considered to be the best method, whereby the waste plastics are melted and transformed into new products. However, only around 20% of the collected material is of sufficient quality to do this (Buegler and others, 2007). The energy in the waste plastics can be recovered, for example, by incineration coupled with power generation or district heating, or via combustion in cement kilns. A third method is feedstock recycling where waste plastics are introduced into processes designed to yield chemical feedstocks rather than heat. This category includes the utilisation of plastics in blast furnaces (BFs). BF usage also recovers energy from the waste plastics and so it is sometimes categorised as energy recovery. The preferred classification in the EU Directive on waste management, though, is recycling rather than energy recovery (Official Journal of the European Union, 2008). Both feedstock recycling and energy recovery can use mixed waste plastics that are not of sufficient quality or are too expensive to be sorted into separate types for mechanical recycling.

BF-based ironmaking processes can utilise waste plastics by:

- carbonisation with coal to produce coke. Nippon Steel, for example, employs waste plastics in their coking coal blends at five of their steelworks;
- top charging into the BF, although this generates unwanted tar from the decomposition of the plastics in the shaft (Assis and others, 1999);
- gasifying the plastics outside the furnace. The resultant synthesis gas is then injected through the tuyeres; or
- injection as a solid through the tuyeres in a similar way to pulverised coal.

The co-injection of waste plastics and coal into BFs is the subject of this report.

Pulverised coal injection (PCI) is a well established technology. It is practised in most, if not all, countries with coke-based BFs, and new BFs are nearly always fitted with PCI capability. Waste plastics injection (WPI) is less

commonly carried out, with only a few ironmaking plants in Japan and Europe currently injecting plastics. The first attempts at WPI were made at the Bremen Steel Works in 1994, with commercial injection starting a year later. The first integrated system for injecting plastic wastes was at NKK's (now JFE Steel) Keihin Works (East Japan Works) in Japan (Ziębik and Stanek, 2001).

Injecting waste plastics into BFs has a number of environmental, operational and economic benefits. These include:

- a reduction in the amount of plastic wastes being landfilled or incinerated. This will help solve the environmental issues associated with these two waste disposal methods, and the need for new landfill sites and incinerators;
- lower consumption of both coke and pulverised coal, thus saving coal resources. Coke forms a major portion of the cost of hot metal. Furthermore, with high WPI (or PCI) rates, coke oven life is extended since less coke is required to be produced. 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. However, neither waste plastics nor coal injectants can completely replace coke and so cokemaking facilities will always be needed in BF-based ironmaking. The amount of coke replaced in the BF will be partly dependent on the quality of the waste plastics and coal;
- energy resource savings. The benefit of saved resources from mixed waste plastics BF injection is around 47 GJ/t. This compares to 0 to 60 MJ/t of waste plastics for mechanical recycling, depending on the process (Buegler and others, 2007; Ecker, 2008; GUA, 2005). In many mechanical recycling processes for mixed waste plastics, such as in roofing tiles, the recycling benefit is actually very small. The energy needed for recycling is equal to the energy credit from the substitution because the substituted material (concrete, wood, roofing tiles) does not require much energy for production;
- decrease in carbon dioxide (CO₂) emissions since the combustion energy of waste plastics is generally at least as high as the pulverised coal normally injected, and their higher ratio of hydrogen to carbon means less CO₂ is produced within the BF from the combustion and iron ore reduction processes;
- lower energy consumption. Hydrogen is a more favourable reducing agent than carbon. The regeneration of hydrogen is faster and less endothermic than carbon monoxide regeneration. Consequently WPI can lower energy consumption, which also means lower CO₂ emissions;
- high energy efficiency of 80% or more. About 60% of the injected plastics are consumed in the reduction of the iron ore, and around 20% of the energy in the remaining 40% of the gases is utilised as a fuel within the steelworks (Ogaki and others, 2001; Wakimoto, 2001).

Consequently, waste plastics can be employed more efficiently in BFs than in plants which directly combust these materials to generate heat or electricity or just incinerate them;

- lower sulphur and alkalis contents than coal. Injectants with low sulphur contents are preferred because of the effects of sulphur on the quality of the hot metal. Alkalis can contribute to coke degradation, sinter disintegration and deterioration of the refractory furnace lining;
- low emissions of dioxins and furans, which are often associated with conventional waste incinerators. Emissions of dioxin at the Bremen Steel Works were 0.0001–0.0005 ng/m³ of exhaust gas, values well below those legislated for German waste incinerators (Assis and others, 1999). Typically, no additional gas contamination arises so the offgas can still be used in power plants (Ziębik and Stanek, 2001) and for other uses around the steelworks.

The main disadvantages of WPI is the cost of the collection and treatment of the material. Waste plastics come from many sources including households, industry and agriculture, and so are widely distributed. Collection is therefore expensive, as is their treatment. The wastes are highly heterogeneous, consisting of mixtures of different types of plastics, such as film from packaging and solid containers, as well as contaminants. Packaging and container wastes require separate processing. Plastics with a high chlorine content, such as polyvinylchloride (PVC), need to be dechlorinated, adding to the preparation costs. Chlorine compounds can corrode the BF refractory lining and the pipelines in the offgas cleaning system. The non-ferrous metals in automotive shredder residues, which contain a high proportion of plastics, have to be removed as they adversely affect the quality of the hot metal product. BF performance is predominantly governed by the quality and consistency of the injectant, coke and iron ore.

This report extends the one by Carpenter (2006) on the use of PCI in BFs. The PCI report concluded 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.’ One of aims of this report is to examine the behaviour of blends of low and high volatile coals in BFs. The main emphasis, though, is on the co-injection of waste plastics, either as a separate stream or blended with coal.

The report begins by outlining the BF process. The quality of the injectants influences the quality of the hot metal, stability and productivity of the BF, and the offgas gas composition. The principal properties of coal and waste plastics that influence these factors are discussed in Chapter 3. The following chapter covers the preparation and injection of coal and plastics. Once injected, the combustion performance of the coal and plastics is important as these could adversely

influence BF operation. The combustion behaviour of coal and waste plastics, including synergistic effects, are discussed in Chapter 5. The following chapters describe the consumption of unburnt char outside the raceway and the transfer of elements that could adversely affect the hot metal quality. Finally, environmental aspects are examined.

The effects of the injection of coal and waste plastics on the technical and economic performance of a steelworks will be site specific. This report therefore concentrates on the technical aspects of their injection, and only covers economic factors in general terms.

2 The blast furnace

To understand the importance of the quality of coal and waste plastics, and the role of these injectants, it is necessary to describe what happens to them within a BF. Coal and waste plastics have two roles. They not only provide part of the heat required for reducing the iron ore, but also some of the reducing gases. This chapter describes a BF and the chemical processes occurring within it. The importance of permeability within the furnace and how the raw materials can affect this parameter is then discussed.

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 molten liquids, travelling down the shaft. Pulverised coal, waste plastics 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.

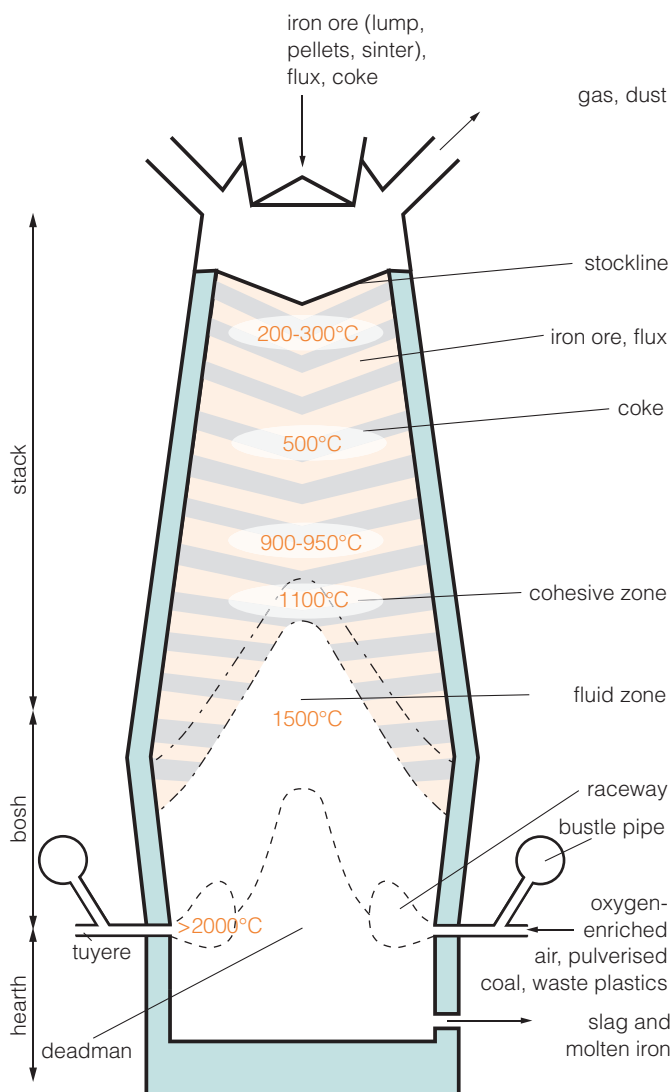


Figure 1 Blast furnace cross section

The iron ore (lump, pellets, sinter), coke and flux (limestone or lime) are alternatively (or, in some cases, simultaneously) charged into the top of the furnace (see Figure 1). 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 500°C, 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 900–950°C, direct reduction of the iron oxide by solid coke occurs. The ore is reduced by CO and H₂, and the carbon dioxide (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 is an important parameter since this determines the temperature range where the transition from indirect to direct reduction takes place.

Lower down the furnace in a region termed the cohesive zone, slag starts to form at around 1100°C. Initially it is relatively viscous, and surrounds the iron oxide particles, preventing further reduction. As the temperature increases to 1400–1450°C, it melts and reduction continues. This region is critical in terms of burden permeability.

In the next zone, termed the fluid or active coke zone, the temperature increases to about 1500°C, continuing to melt the iron ore and slag. There is considerable movement in this region and the coke feeds from it into the raceway. The raceway is the hottest part of the furnace, where temperatures can reach 2200°C. It is created when hot air is injected through tuyeres into the furnace. Pulverised coal and waste plastics are injected with the hot air blast directly into the raceway. Combustion and gasification of the coal, waste plastics and coke occurs (see Chapter 5), 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. A furnace with a hearth diameter of 14 m may have up to 50 tuyeres, each with its own raceway, arranged symmetrically around its periphery. The depth of each raceway is typically 1–2 m, depending on the kinetic energy of the hot blast.

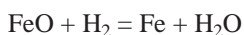
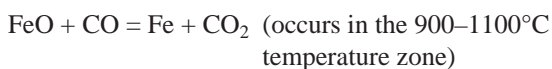
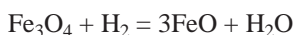
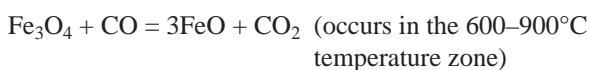
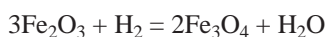
Unburnt material exits the raceway and passes up the furnace into the bosh and stack. The molten metal and slag pass through the deadman (stagnant coke bed) to the base of the furnace where they are removed through the taphole. The slag is then skimmed off from the molten iron. Some furnaces have separate 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. Good performance of a steel plant requires a consistent hot metal quality (see Chapter 7) and the temperature of the hot metal should also be as high as possible.

The hot gas leaving the top of the furnace (offgas or top gas) is cooled, cleaned, and utilised 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

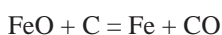
The BF can be considered as a countercurrent heat and mass exchanger as heat is transferred from the ascending gas to the burden, and oxygen from the descending burden to the gas. The countercurrent nature of the reactions makes the overall process an extremely efficient one (Geerdes and others, 2004).

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 to metallic iron. This simply means the removal of oxygen from the iron oxides by a series of chemical reactions (termed *gas reduction* or *indirect reduction*) as follows:

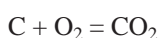


These reactions generate heat (exothermic). At the same time as the iron oxides are going through these reactions, they are also beginning to soften and melt.

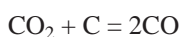
At the high temperatures near the fluid zone, carbon (coke) reduces wüstite (FeO) to produce iron and carbon monoxide. This reaction, termed *direct reduction*, is highly endothermic, and the heat that drives it is provided by the specific heat contained in the hot raceway gas:



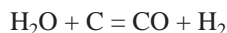
Combustion and gasification of coal, coke and plastic wastes generate the reducing gases (CO and H₂) that flow up the furnace. As coal and coke enter the raceway they are ignited by the hot air blast and immediately combust to produce carbon dioxide and heat:



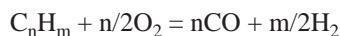
Since the reaction takes place in the presence of excess carbon at a high temperature, the carbon dioxide is reduced by the *Boudouard* or *solution loss reaction* to carbon monoxide (an endothermic reaction):



In addition, water vapour produced during combustion is reduced as follows (an endothermic reaction):

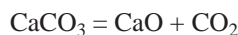


Similarly, the injected waste plastics are broken down to form CO and H₂:



Injection of H₂-bearing materials enhances indirect reduction. H₂ is a more effective reducing gas than carbon (direct reduction). The H₂ regeneration reaction (H₂O + C = CO + H₂) is less endothermic and proceeds faster than CO regeneration, the Boudouard reaction. Higher H₂ contents in the BF promote higher rates of iron oxide reduction, and hence increases productivity. Waste plastics generate more H₂ than coal since they basically consist of carbon and hydrogen. With more H₂ available from the waste plastics contributing to the reduction process and with steam (H₂O) as the gaseous reduction product, the amount of CO₂ generated is lowered by approximately 30% in comparison with the use of coke and coal alone (Li and others, 2007; Ogaki and others, 2001). As well as lowering CO₂ emissions, energy consumption decreases since the endothermic Boudouard and direct reduction processes are diminished. Unfortunately, a higher H₂ concentration can lead to higher amounts of coke fines in the furnace shaft.

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



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, coal and, if present, waste plastics.

2.3 Process issues

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 increasing rates of coal and waste plastics injection are a response to permeability requirements. Some of the issues for waste plastics are shown in Figure 2. They are essentially the same as those for high PCI rates (*see* Carpenter (2006)), and consequently, for co-injection of coal and waste plastics.

Permeability within the furnace is influenced by the properties of the iron ore burden, coke, coal and plastic wastes. Fines generated from these materials can accumulate, blocking both gas and liquid flows. Unburnt char from coal and waste plastics (*see* Chapter 5) and coke fines, for example, can accumulate in the bird's nest, a relatively compact zone between the raceway and deadman, and around

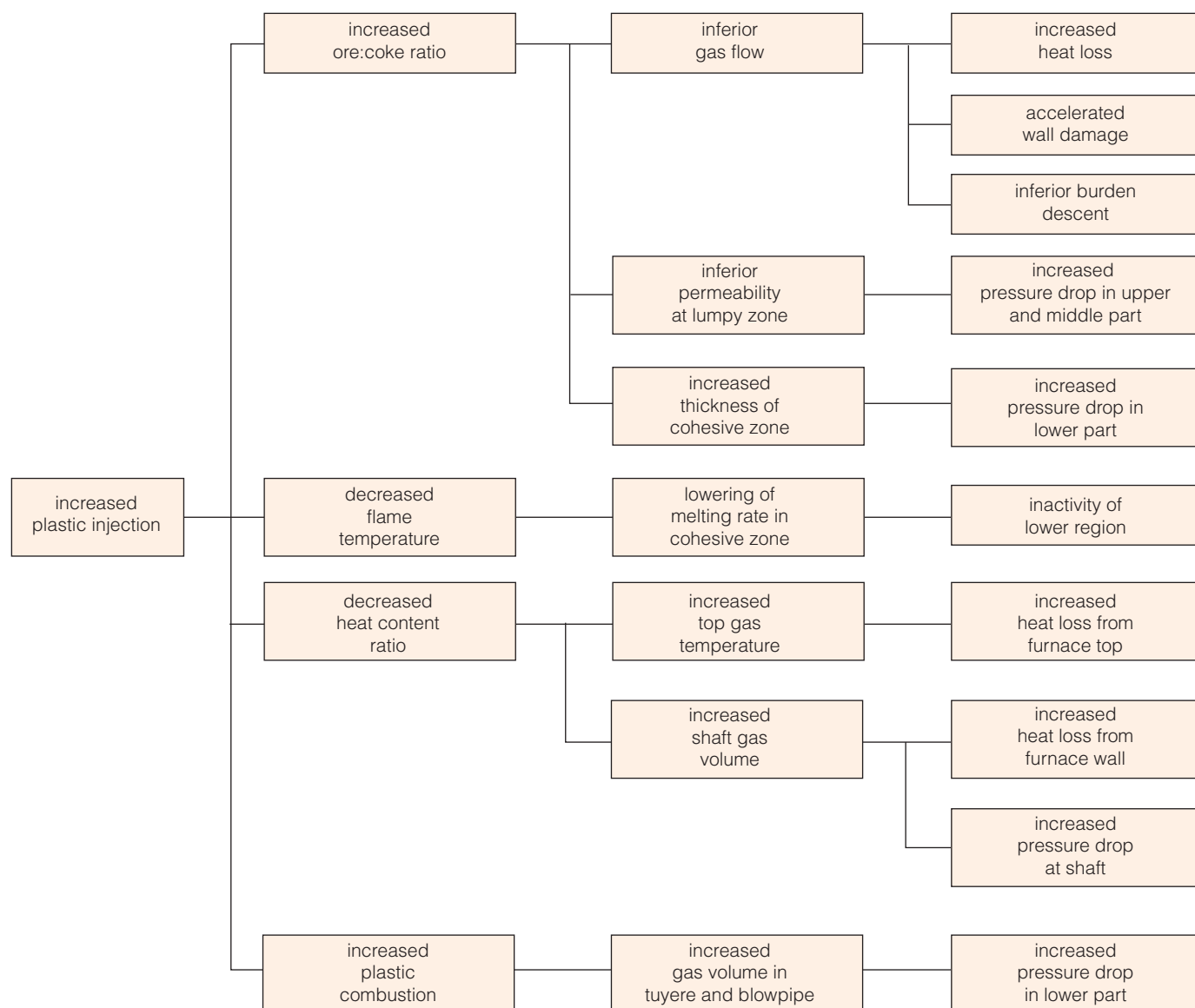


Figure 2 Expected technical issues with increasing injection rates of waste plastics (Heo and others, 2000b)

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. The importance of coal and waste plastic properties are discussed in the following chapter, and those for iron ore and coke in the following sections.

2.3.1 Iron ore

The more the gas removes oxygen from the iron ore burden, the more efficient the process. Consequently, intimate contact between the gas and ore burden is important. To optimise this contact the permeability of the ore layer must be as high as possible. The ratio of the gas flowing through the ore burden and the amount of oxygen to be removed from the burden should also be in balance (Geerdes and others, 2004).

The permeability of an ore layer is largely determined by the amount of fines (under 5 mm) within it. The majority of the

fines are generally generated by sinter, if it is present in the charged burden, or from lump ores (Geerdes and others, 2004). There are two sources of fines, those that:

- form part of the iron ore charge. Thus it is important to screen the burden materials to remove the fines before they are charged into the furnace. The preferred size range for the charge is typically 5–50 mm for sinter, 8–16 mm for pellets and 6–60 mm for lump ore (Carpenter, 2006). The majority of BFs operating today at high PCI rates use a large proportion of prepared iron ore, over 80% pellets and/or sinter. Sinter burdens are prominent in Europe and Asia, while pellet burdens are used in North America and Scandinavia (Geerdes and others, 2004);
- are generated by degradation of the iron burden materials during transport and charging, and within the furnace shaft. It is therefore important to control the burden's degradation characteristics. There are standard tests for determining the resistance of the iron burden materials to physical degradation by impact and abrasion, and for measuring disintegration during reduction at low temperatures (*see* Carpenter, 2006).

Iron ore with a high reducibility is preferred. Again, there are various standard methods for determining iron ore reducibility. 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.

As soon as the burden material starts softening and melting, the permeability for gas flow reduces. Therefore, the burden materials should start melting at relatively high temperatures so that they do not impede gas flow while they are still high up in the stack. A fast transition from the solid to liquid state is also preferred. Melting properties are determined by the slag composition. Melting of pellets and lump ore typically starts at 1000 to 1100°C, whilst basic sinter begins melting at higher temperatures (Geerdes and others, 2004).

The quality of the burden material should be consistent to ensure stable BF operation, and it should be distributed into the BF in such a way as to achieve smooth operation with high productivity.

2.3.2 Coke

Coke performs three main roles in a BF:

- chemically, it is a reducing agent. Its combustion provides 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 and plastic wastes 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. Because of the physical role of coke, there is a limit to the amount of coal and plastic wastes that can be injected.

A high (and consistent) coke quality is needed to decrease fines generation that could lead to poor permeability, unstable BF operation, and lower productivity. The rate at which the coke degrades and generates fines as it descends through the furnace is mainly controlled by the Boudouard 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 (within the furnace), and resistance to breakage and abrasion during handling. Shattering and abrasion mechanisms dominate fines generation in the

upper part (stack) of the furnace, and these mechanisms are often related to the coke cold strength. Standard tests for assessing the mechanical degradation (cold strength) of coke are covered in Carpenter (2006);

- hot strength, and the retention of structural integrity in the coke lumps when reacted with CO₂ at high temperatures. The reaction of coke with CO₂ (Boudouard reaction) in the raceway promotes its degradation and the production of fines. In addition, degradation caused by impact with the high speed hot blast can occur. Inferior coke can result in distorted raceway and cohesive zones, and accumulation of coke fines in the deadman leading to permeability problems. Consequently, the strength and stability of the coke structure after its reaction with CO₂ 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), determined using standardised tests (*see* Carpenter, 2006);
- chemical composition, particularly its ash, sulphur (which contributes to hot metal sulphur content) and alkali contents. Alkalis (and other basic oxides such as iron oxides) increase the coke's reactivity towards CO₂ due to their catalytic effect, and lower its abrasion resistance. Thus the coke is more susceptible to degradation. The effect of minerals in coke on its performance in the BF has recently been reviewed by Gupta and others (2008);
- mean size and size distribution. Undersize material has to be screened out before charging to avoid potential permeability problems. The size distribution impacts directly on furnace permeability, both in the stack area and the lower parts of the furnace. The average mean size of charged coke is typically in the range 45 to 55 mm (Geerdes and others, 2004).

Under stable operation, the majority of the coke fines are consumed within the furnace by the Boudouard reaction, hot metal carburisation and reaction with the slag, with only a small amount exiting with the offgas.

Coke rates of below 300 kg per tonne of hot metal (thm) have become state-of-the-art practice in European blast furnaces with PCI. The lowest values of coarse coke are around 240 kg/thm. The use of nut coke is becoming common, the amount depending on local conditions. Nut coke increases the overall carbon yield of the ironmaking plant and can protect coarse coke from excessive size degradation as it is preferentially gasified in the shaft (Steiler and Hess, 2006). However, tests carried out at a commercial BF using ZrO₂-labelled nut coke showed that nut coke was not preferentially consumed (Janhsen and others, 2007).

3 Quality of coal and waste plastics

The composition and properties of the injectants can influence the operation, stability and productivity of BFs, the quality of the hot metal product, and the offgas composition. This chapter discusses the availability of coal and waste plastics, and their principal properties that affect the performance of BFs. It is important that the quality of the coal and waste plastics injectants is consistent to ensure stable BF operation.

3.1 Coal

There are ample quantities of good quality coal available for PCI. Global coal reserves were 847,488 Mt at the end of 2005 (Trinaman and Clarke, 2007). These are proven recoverable reserves – the geological resource is far larger. The proven reserves are estimated to last for around another 150 y at the current rate of production. This compares to about 56 y for proven natural gas reserves, and even less for oil. Coal deposits are widely distributed around the world, with economically recoverable reserves available in more than 70 countries. The top five countries are the USA with 242,721 Mt of proven recoverable reserves, followed by the Russian Federation (157,010 Mt), China (114,500 Mt), Australia (76,600 Mt) and India (56,498 Mt). World consumption of PCI coals has been growing over the years

(see Table 1). The Table is not comprehensive as some countries practising PCI, such as China, are not included. The major consumer in 2007 was Japan, followed by Korea, Germany, France and India.

3.1.1 Coal types and blends

A wide range of coals, ranging in rank from high volatile (HV) lignite to low volatile (LV) anthracite, have been successfully injected. Coal types for PCI are often discriminated by their volatile matter content. Coals that have between 6 and 12% volatile matter are generally classified as low volatile (LV), those between 12 and 30% as mid volatile (MV) and those over 30% are high volatile (HV) (Geerdes and others, 2004). Whilst the coal type seems to have little significant impact on BF operation at low injection rates, that is, below 100 kg/thm, coal properties become more important as injection rates increase. Interactions between the coal and co-injected plastics can also occur.

Selection of coals for injection is a complicated process that often involves compromises. The performance of a given coal is largely judged based on cost savings, and this depends on coal acquisition costs and on the chemical and physical

Table 1 World consumption of PCI coals (kt) (IEA, 2009)

	2001	2002	2003	2004	2005	2006	2007
Belgium	933	744	646	591	479	469	403
Colombia	231	215	336	231	233	198	198
France	1840	2061	1990	2103	2373	2541	2453
Germany	2262	2287	3060	2641	2770	2975	3115
India	2119	2328	2428	2059	2160	2266	2377
Italy	714	697	771	955	1154	1299	829
Japan	11165	11045	11097	10416	10440	10670	11594
Korea	3741	4663	5005	5065e	5481	5603	6284
Netherlands	1207	1235	1330	1406	1472	1289	1559
New Zealand	701	686	780	864	798	814	788
Slovakia	488	404	380	385	377	470	468
Spain	575	495	360	405	493	362	568
Sweden	442	398	363	423	417	426	426
UK	683	665	815	821	975	1000	1109
USA	2425e	1988	1850	1733	1252	1408	1550
Total world	29526	29911	31211	30108	30874	31790	33987

e estimated

Note: not all countries that consume PCI coals are included

Table 2 Indicative PCI coal specifications (Carpenter, 2006; Sharma, 2004)

	Kumba Coal (South Africa)	Gijón Works (Spain)	Port Kembla (NSW, Australia)	Great Lakes Works (MI, USA)	ThyssenKrupp Stahl (Germany)	Kobe Steel (Japan)	Tata Steel (India)
Coal		HV + LV blend	HV + MV blend		blend		
Volatile matter, %	20–38	25	26.9 (db)	32–38	19–23 (db)	10–45	24–27 (db)
Total moisture, %	6–8	8.2	1.85 (ad)	<10	0.9 (db)	<13	<10
Ash, %	<8	8.3	10 (db)	<10	8.55 (db)	<10 (db)	10–12 (db)
Sulphur, %	<0.8	0.64	0.47 (db)	<1	0.38 (db)		<0.65 (db)
Phosphorus, %	<0.05	0.01		<0.025	0.03 (db)		<0.06 (db)
Alkalis, % (Na ₂ O, K ₂ O)	<0.2			<0.35	0.14 (db)	depends on total alkali input from all sources	
HGI	45–70	63	57	40–60	50–60	>30 (single) >40 (blend)	>60
Ash fusion temperature, °C		1311 (ST)	>1550 (IDT)	1315–1482	1350–1650 (IDT)	>1375 (HT)	>1300
Calorific value, MJ/kg		33.9 (gross)	30.9 (gross, ad)		33 (gross, ad) 31 (net, db)		>25

properties of the coal (Lherbier and Serrano, 2009). The required properties are stipulated in the coal specification. Each specification and the relative importance of the coal properties within it are site specific. A number of different operational factors determine which properties the BF operator views as essential; these may relate to both BF operation and PCI preparation. Indicative PCI coal specifications are given in Table 2.

Coals are often blended to meet the requisite specification. Blending can optimise the relative strengths of the constituent coals, diluting unfavourable properties, and reduce raw material costs since cheaper coals can be incorporated. The quality of the blend should be consistent to ensure stable BF operation. However, blending different types of coal, such as low and high volatile coals, can lead to problems. The blends may not behave as an average of their components, but may be affected disproportionately by one coal with problem characteristics. Factors that need to be considered include:

- the grinding behaviour of the blend. Preferential grinding of the softer coal can occur (*see* Section 4.1.4); and
- combustion behaviour. The individual coals can combust at different temperatures and at different times, and burn out at varying rates (*see* Section 5.2.1).

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 described under the relevant property in the discussion below, and is covered in more detail in the report by Carpenter (1995).

Coke replacement ratio

The amount of coke that can be replaced by the injected coal

(and waste plastics), that is, the coke replacement ratio, and the coal/waste plastics price have the largest impacts on the economics of injection. The coke replacement ratio (RR) is defined as the mass, in kilograms, of coke replaced per kilogram of coal (or waste plastics), 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 and oxygen enrichment. This is the value normally quoted in the literature (Bennett, 2007; Jaffarullah and Ghosh, 2005). 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.

The RR depends on a complex interplay of chemical and physical processes and is influenced by:

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

Various equations have been derived relating coke RR to the properties of coal. Bennett (2007) provides details of some of these calculation methods. In general, the RR increases with coal rank (*see* Table 3). The Table also indicates the effect of coal rank on the RAFT, discussed in Section 5.2.1.

Deno (2000) discusses the maximum possible PCI rate. For instance, at a minimum stoichiometric oxygen ratio of

Table 3 Coke RR and cooling characteristics of different coal types (Hutny and others, 1997)

Coal type	RR	RAFT change, °C/kg	CV, MJ/kg
Anthracite	0.99	0.82	32.6
LV bituminous	0.90	1.00	33.5
MV bituminous	0.86	1.17	32.6
HV bituminous	0.73	1.66	29.7
Subbituminous	0.65	1.84	23.9
Lignite	0.50	1.99	23.4

0.6–0.7, the minimum coke rate is 270–280 kg/thm and the maximum PCI rate would be 180–270 kg/thm.

3.1.2 Coal properties and evaluation

Potential injection coals can be evaluated on the basis of ‘value-in-use’, where all the effects on cost are taken into account, including the coke RR, coal properties, coal delivery costs and what the operators want the BF to achieve. There may, for example, be an emphasis on offgas energy utilisation within the BF or for export, or limits on the pulveriser capacity (where the coal’s grindability properties become important). Site specific cost issues therefore dictate that no two methods will be the same. Each company has its own value-in-use model, which is usually confidential. Some plants purchase at least one coal that could be used for both PCI and cokemaking. This allows flexibility in the blend and saves on stockpile space requirements.

The desire for a high coke RR without affecting furnace productivity and hot metal quality places a relatively tight specification on some of the coal properties. This Section looks at the principal properties utilised in a coal specification (see Table 2). More information about these and other coal properties can be found in Carpenter (2006). The effect of some of these properties are also relevant to waste plastics.

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 condensable volatiles, mainly tar. VM yield generally increases with decreasing rank, and the proportion of incombustible gases increases as coal rank decreases. In addition, the maceral composition affects VM yield and composition, with liptinite producing more VM than vitrinite which, in turn, produces more than inertinite (Carpenter, 1995). 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 coke fines generation in the raceway. This is due to coal devolatilisation in the hot blast and the action of the volatiles liberated in the tuyeres. 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:

- LV coals give higher coke RRs, and hence lower coke rates, coupled with minimum cooling (VM production is endothermic). They produce a lower volume of offgas with a lower calorific value, less H₂ for iron ore reduction, a higher RAFT and have a lower combustion efficiency than HV coals (although there are exceptions);
- HV coals generally have superior combustion performance due to higher volatile release, a lower ignition temperature and produce more reactive chars (hence better burnout) than LV coals. However, inertinite-rich LV coals, such as the Australian Permian coals, can also produce reactive chars (see Section 5.2.1). Unburnt char can reduce bed permeability and lead to carbon losses through the offgas. 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 H₂ for reducing the iron ore. The higher gas volume, though, may lead to back pressure problems in the tuyere. HV coals are more susceptible to spontaneous combustion affecting the ground handling system.

The blast temperature and/or the oxygen enrichment rate can be adjusted to suit the injected coal. 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, although the caveats listed for blends in Section 3.1.1 need to be considered. Some care in the use of the additivity rule for VM may be required. 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).

Moisture

Moisture in coal:

- increases transportation costs;
- affects the handleability of coals. Coals with poor handling properties can cause blockages during transport to the BF, such as pluggage of belt conveyors and chutes. Usually, as the surface moisture increases, so does the difficulty in handling the coals, especially when combined with a high coal fines content. Blockages during transport to the injection lances have also been linked to the moisture content of the pulverised coal (see Chapter 4);
- affects both the energy consumption and output of the pulveriser by increasing the volume and temperature of the air needed for adequate coal drying (see Section 4.1.1);
- influences the RAFT. A higher moisture content tends to lower the RAFT and requires more energy for evaporation of the moisture.

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. Moisture content is considered to be additive. In general, a total moisture content of less than 10% is preferred for PCI coals.

Ash content

At high PCI rates, the injected coal/blend becomes a major source of ash and other impurities. An ash content of less than 10% is normally preferred because:

- high levels of coal mineral matter can reduce pulveriser performance and throughput, and increase wear in the pulveriser and conveying pipelines (*see* Section 4.1);
- lower slag volumes, and therefore a better thermal efficiency, are attained. Less energy is needed to melt the ash in lower ash materials;
- high levels of ash 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 coal ash content. This arises from the requirement to add additional carbon to compensate for the extra ash; and
- to limit undesirable constituents present in the ash, such as silica, alumina and chlorine.

Some care in the application of the additivity rule for ash content is required when blending coals of widely different rank (Carpenter, 1995).

Ash composition

The constituents in the coal mineral matter can influence furnace operation and the quality of the hot metal product. They can affect ash viscosity. Coal ashes with high viscosity at high temperatures (around 1600°C) can cause permeability problems in the lower part of the BF, mainly in the neighbourhood of the combustion zone, or in the active coke zone or on the deadman surface (Defendi and others, 2008). The inorganic constituents of interest include:

- alumina (Al_2O_3), which is considered to be responsible for the largest increases in flux requirements. High alumina contents in coal increase the amounts in the BF slag, which can cause problems for slag utilisation in the cement industry;
- silica (SiO_2). Coals with low silica (SiO_2) in the ash are favoured to help ensure that the slag formed can be easily tapped from the furnace. A low silica load at the tuyeres results in lower amounts of gaseous silicon monoxide (SiO), and hence a lower hot metal silicon content (*see* Section 7.1). Coal char consumption is also influenced by its silica content (*see* Section 6.1);
- alkalis. Sodium- and potassium-containing compounds can contribute to coke degradation, sinter disintegration and deterioration of the refractory furnace lining. Removal of alkalis by slag requires lowering both slag basicity and flame temperature, conditions opposite to those needed for a low sulphur metal product. The combined upper limit for sodium and potassium oxides is usually 0.1%, ad, for coals;
- chlorine, which, mostly in the form of alkali chlorides, is associated with refractory deterioration. Unprotected metal components can be corroded by chlorine exiting in

the offgas as HCl. The rest of the chlorine is removed in the molten slag (and limestone flux). The partitioning of chlorine between the offgas and molten slag depends on process conditions. The limit for coal chlorine is typically 0.05% ad. However, chlorine inputs have reached 1 kg/thm in the Dillinger BFs in Germany where chlorine-rich coals are injected (Lectard and others, 2003);

- phosphorus, as it affects product quality. A coal phosphorus content below 0.05% is usually preferred;
- sulphur because of its effect on the furnace sulphur loading and hot metal quality (*see* Section 7.2). Blast furnace slag is a good desulphuriser. Nevertheless, if coal injection increases the amount of sulphur in the furnace, additional operating costs are incurred associated with greater slag volumes, modifying the slag basicity and/or taking additional hot metal desulphurisation measures outside the furnace. It is difficult to remove sulphur and alkalis simultaneously within the BF as sulphur removal requires a basic slag and alkalis an acidic slag. The limit for coal sulphur is typically below 0.8%.

Ash composition values, including chlorine and sulphur contents, are probably additive for coal blends.

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. Due to design limitations, some BFs require a low IDT to help ensure that the slag formed in the furnace is easily tapped. High IDT coals could block the deadman if the ash does not melt with the deadman slag. The softening temperature (ST) or hemispherical temperature (HT), both higher than the IDT, may be specified instead (*see* Table 2 on page 12).

The IDT is a reflection of the coal ash composition. The presence of alkaline oxides (CaO , MgO , Fe_2O_3 , FeO) act as fluxes, lowering the melting temperatures, especially in the presence of excess SiO_2 . High sulphur (from pyrite) can result in a lower IDT. HV coal ash, such as 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. IDTs are non-additive for coal blends.

HGI

Coal grindability is typically determined by the Hardgrove grindability index (HGI). The index is traditionally used to predict the capacity, performance and energy requirement of pulverisers, as well as determining the particle size of the grind produced (*see* Section 4.1). Generally, the higher the HGI, the easier the coal is to grind, with consequent lower power consumption and higher throughput of coal in the pulveriser. The resultant size distribution of the coal can affect its combustibility (*see* Section 5.3.1) and coal handleability in the bins and transfer lines. HGI increases to a maximum as coal rank increases from subbituminous to medium-rank coals and thereafter decreases as rank increases to anthracite.

Soft coals may produce a high proportion of fines which could clog transport lines, whilst hard (low HGI) coals can be

difficult to grind, leading to increased operating and maintenance costs. Hence coals with an HGI between 40 and 70 are usually preferred. This also helps to minimise breakage during handling and injection. HGIs are not generally additive unless the blend contains petrographically similar coals with similar HGI values. Furthermore, HGI is not always a good indicator of grinding performance (*see* Carpenter, 2002); coals with similar HGI values may not, in practice, perform identically.

Calorific value

The calorific value (CV) of coal influences:

- the coke RR. In general, RR increases as coal CV increases (*see* Table 3 on page 13);
- furnace stability. Higher CV coals should increase the heat flux in the raceway and consequently, the RAFT.

Typically, CV increases with coal rank (decreasing VM content) and is additive for blends.

Coal evaluation

Most of the coal properties described above are determined by laboratory methods specified in national and international standards and these are discussed in Carpenter (2002). 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 900/950°C, slow heating rate and a residence time of minutes) differ significantly from those occurring within the BF raceway (with temperatures around 2200°C, heating rates of 10⁵–10⁶ °C/s, residence time of 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 the different national and international standards, and so the standard followed should be stated.

Tests therefore need to be developed that better simulate the conditions within a BF. 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.

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 milligramme or gramme samples used in standard and non-standard bench-scale tests can provide a truly representative sample of the tonnes of coal consumed within 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.

3.2 Waste plastics

Plastics production and consumption worldwide has grown from around 1.5 Mt in 1950 to 260 Mt in 2007, increasing at an average rate of about 9% per year. However, production dropped in 2008 to 245 Mt due to the global financial crisis. Figure 3 shows world plastic production, broken down by country/region. One major production region is Europe (the 27 member countries of the European Union (EU27), plus Norway and Switzerland), which produced about 25% (60 Mt) of the world's output in 2008 (PlasticsEurope, 2009). Both Austria and Germany (part of the EU27) inject waste plastics into BFs (*see* Table 4). The only other country currently injecting waste plastics is Japan. Pohang Iron and Steel Company (POSCO) in Korea initiated WPI (with a size up to 5–6 mm) at one of its BFs in 1996, but discontinued due to economic and combustibility issues (Kim and others, 2002; Sahajwalla and others, 2004). Trials with WPI were also carried out by ThyssenKrupp Stahl in Duisburg, Germany (Lüngen and Theobald, 1997). Baosteel in China is investigating the processing, transport and combustion characteristics of waste plastics, and their co-injection with coal. A trial injection of waste plastics in a single tuyere at BF3 was successfully undertaken (Baosteel, 2008). According to Al-Salem and others (2010), a programme investigating WPI in a small BF is being sponsored by the Ministry of

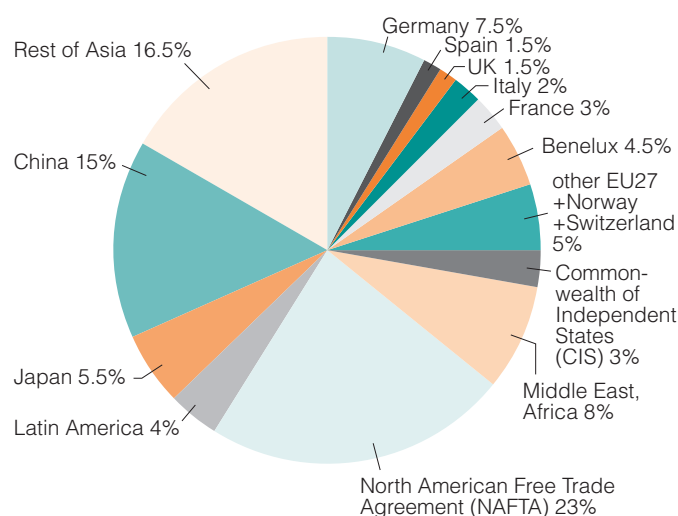


Figure 3 World plastics production (245 Mt) in 2008 (PlasticsEurope, 2009)

Table 4 Blast furnaces injecting waste plastics

Works name/BF	Location	Owner (former name)	Injectants	Waste plastics capacity, t/y	Start-up date	Comments
Voestalpine BF A	Linz, Austria	voestalpine Stahl GmbH	heavy oil/crude tar + waste plastics (from packaging, commercial and household waste, shredder residue)	220,000	2007	pilot trials in 2005 and 2006, approval for commercial use in 2007
Stahlwerke Bremen BF 2 and BF 3	Bremen, Germany	ArcelorMittal Bremen GmbH (Stahlwerke Bremen GmbH)	heavy oil + waste plastics (agglomerated)	70,000	Feb 1994 (BF 2, first test at 46 t/month) Sep 1996 (BF 3)	waste plastics injected through 8 of the 32 tuyeres in BF 2, and 8 of the 24 tuyeres in BF 3; can use plastic waste with a chlorine content $\leq 1.5\%$ (about 3% PVC); injected 110,000 t in 2002; ceased WPI and started PCI in Apr 2004 at BF 2 and Oct 2006 at BF 3
Eisenhüttenstadt BF 1	Eisenhüttenstadt, Germany	ArcelorMittal Eisenhüttenstadt GmbH (EKO Stahl GmbH)	heavy fuel oil + agglomerated waste plastics + animal fats + coal	45,000	1997	pilot tests in BF 6 (1992-1996); plastics injected in BF 3 until May 2001; in 2004 injected 67 kg/thm agglomerated waste plastics + 16 kg/thm heavy fuel oil
Stahlwerke Dortmund BF 4	Dortmund, Germany	ThyssenKrupp Stahl GmbH (Krupp Hoesch Stahl GmbH)	coal + waste plastics		1996	EU Joule III project injecting coal-plastic blend; terminated in 1997 due to technical reasons and poor economics
Salzgitter BF C	Salzgitter, Germany	Salzgitter Flachstahl GmbH	heavy oil + waste plastics (including ASR)	50,000	2008	injecting waste plastics ~5 t/h with a chlorine content <1.5%
West Japan Works, Fukuyama BF 3 and BF 4	Fukuyama, Japan	JFE Steel Corp (NKK Corp)	coal + waste plastics (from container and packaging waste)	30,000	Apr 2000	waste plastics recycling plant at Fukuyama
East Japan Works, Keihin BF 1	Kawasaki, Japan	JFE Steel Corp (NKK Corp)	coal + waste plastics (from container, packaging and industrial waste)	40,000	Oct 1996	waste plastics recycling plant at Keihin; ceased in Mar 2004
East Japan Works, Keihin BF 2	Kawasaki, Japan	JFE Steel Corp	coal + waste plastics (from container and packaging waste)	30,000	Apr 2004	waste plastics recycling plant at Keihin
Kakogawa Works BF 3	Kakogawa, Japan	Kobe Steel Ltd	coal + waste plastics (from container and packaging waste)	10,040	Feb 2000	

Environment and Forests in India. The following discussion will only covers the countries that are practising WPI at a commercial scale.

The demand for plastics by European converters (EU27 plus Norway and Switzerland) was 48.5 Mt in 2008 (PlasticsEurope, 2009). Figure 4 gives a breakdown of the

demand by end use sector. It shows that packaging is the biggest end use for plastics, as was the case in previous years. The majority of recycled waste plastic therefore comes from the wide field of packaging, which typically has a short service life. In Japan, containers and packaging formed 47% (4.67 Mt) of the total amount of plastic waste (9.94 Mt) produced in 2007 (PWMI Newsletter, 2009).

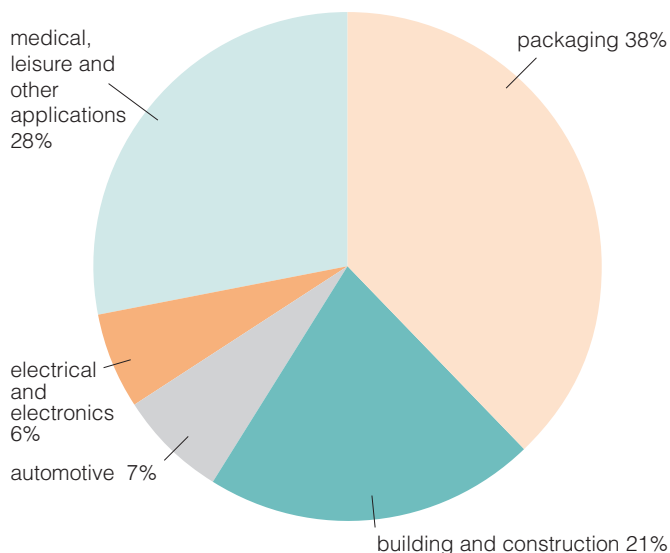


Figure 4 Plastics demand by end use
(PlasticsEurope, 2009)

Legislation in various countries is driving the need to recycle as much as possible. Japan is dependent on foreign sources of natural resources and consequently, recycling and the effective utilisation of wastes is an important issue. Recycling of plastic bottles began in April 1997 after the Container and Packaging Recycling Law was enacted in 1995 (and fully implemented in April 2000). Other recycling legislation includes the Home Appliance Recycling Law (in force from April 2001), End-of-life Vehicle Recycling Law (in force from Jan 2005) and the Construction Material Recycling Law (in effect from 2002). Japan started injecting waste plastics into BFs in 1996, and in 2004 injected 56,000 t into BFs (Japan Plastics Industry Federation, 2006). JFE Steel has injected some 480,000 t of waste plastics over the period 2000-07 (Asanuma and others, 2009). The steel industry worldwide is facing increasing pressure to minimise its impact on the environment by improving the efficiency of energy and resource utilisation. The Japan Iron and Steel Federation has set a target to reduce average energy consumption by 10% during 2008-12 from the 1990 baseline (assuming annual crude steel production of 100 Mt). A supplementary target is for the steel industry to utilise 1 Mt/y of waste plastics, equivalent to an additional 1.5% energy saving. This is conditional on the establishment of an adequate collection system (Anyashiki and others, 2007; Asanuma and others, 2009).

Germany was the first country to inject waste plastics commercially, encouraged by the Ordinance on Packaging Waste (Verpackungsverordnung), which came into force in June 1991 (amended 1998), and the subsidised waste recycling system, Duales System Deutschland. The European Union (EU) has a number of directives concerning waste management, such as those for packaging waste (Directive 94/62/EC of 20 Dec 1994), recycling of end-of-life vehicles (Directive 2000/53/EC of 18 Sep 2000), and for waste electrical and electronic equipment, WEEE (Directive 2002/96/EC of 27 Jan 2003). A new directive on waste management has been published (Directive 2008/98/EC of 19 Nov 2008), that has set out new recycling targets to minimise waste sent to landfill (Official Journal of the

European Union, 2008). It has widened the definition of recycling and recovery. It looks as if recycling now encompasses feedstock (also called chemical) recycling, and hence the recycling of waste plastics in BFs. This may encourage the injection of waste plastics in European BFs. The amount of plastics recycled in BFs is very low (<2% of total waste plastics recycling in Europe and <3% in Japan). BFs recycle plastic materials that are not suitable for reuse (mechanical recycling).

An international standard (ISO 15270:2008) has recently been published that provides guidance for the development of standards and specifications covering plastic wastes recovery and recycling. The recovery technologies covered include material recovery (mechanical recycling, chemical or feedstock recycling, and biological or organic recycling) and energy recovery in the form of heat, steam, or electricity generation. Standards for the characterisation of plastic wastes are also being developed, such as the European standard EN 15347:2007.

3.2.1 Types of plastics

Most plastics are made from simple hydrocarbon molecules (monomers) derived from oil or gas. These undergo polymerisation to form more complex polymers from which products are manufactured. Additives, such as antioxidants, colourants and other stabilisers, are used to give the plastics specific properties. The term plastics describes a range of materials and compounds. There are over 20 distinct groups of plastics with hundreds of varieties. These can be categorised into two main types, namely thermoplastics and thermosets. The latter are plastics that have been hardened by a curing process. Once set they cannot be softened by heating and so are unsuitable for BF injection. They include polyurethane, epoxy and phenolic resins.

The main type of plastics of interest for BF operators are the thermoplastics, that is, those which soften when heated and harden on cooling. These consist of five main families, which account for the majority of plastic demand in the world (around 75% of all plastic demand in Europe):

- polyethylene (PE), which includes low density polyethylene (LDPE) and high density polyethylene (HDPE). LDPE is used for products such as cling film and flexible containers, whilst HDPE is utilised in bottles, pipes, toys and other products;
- polypropylene (PP) employed, for example, in yoghurt pots, upholstery for furniture and automotive parts;
- polyethylene terephthalate (PET) found, for example, in bottles, carpets and food packaging;
- polyvinylchloride (PVC). Applications include window frames, pipes, bottles, automotive parts and medical products; and
- polystyrene (PS), in the form of solid PS and expanded polystyrene (EPS). EPS is used mainly as an insulating material in the construction industry, as an insulator for disposal food containers and protective packaging.

The principal waste streams from which waste plastics are drawn for injection into BFs are municipal solid wastes

(MSW), packaging (both municipal and industrial), WEEE (such as computers, mobile phones, televisions and refrigerators), and end-of-life vehicles (ELV) in the form of automotive shredder residue (ASR). ASR, also known as fluff, is the material left over after an automobile has been shredded and the ferrous metal and other marketable materials have been separated. It contains a significant proportion of polymers (*see* Section 4.2). The need to recycle ASR has increased with landfilling banned in countries such as Germany. The BFs where WPI was first carried out utilised plastics from packaging and containers (in Germany and Japan). Plastics from ASR have been incorporated in the waste plastics feed at the more recent BF A in Linz, Austria. BFs inject mixed waste plastics but this is not always defined. One commonly used definition is that mixed plastics includes all non-bottle plastic packaging.

3.2.2 Properties

Waste plastics are highly heterogeneous materials. They mostly consist of hydrocarbon polymers that are combustible (and additives). It has been estimated that only 3% of the total carbon used as a reducing agent remains non-oxidised (Delgado and others, 2007). The polymers have different physical and chemical properties. The chemical composition of the main polymer groups are given in Table 5. Injectants consist of mixtures of these polymer groups (and, in addition, may contain PVC). The Table therefore includes the composition of a typical waste plastics mixture, in this case, the injectant at the Stahlwerke Bremen works. For comparison purposes, the chemical composition of a fuel oil injectant, also utilised at the Stahlwerke Bremen works, and a pulverised coal are given.

The mixed waste plastics have to meet certain specifications. Kobe Steel's specification is 3% moisture or less, 0.4% chlorides or less and a particle size of 8 mm or less. There are limits on the amount of heavy metals and trace metals in the waste plastic mixture, as these can affect the quality of the hot metal product. One source of the heavy metals is from ASR. Table 6 gives the specification used by voestalpine Stahl where a mixture of waste plastics from packaging, commercial and household waste, and shredder residue is injected. The following is a summary of the main properties

of waste plastics. The influence of these properties on the operation and performance of BFs is discussed in more detail in Section 3.1.2.

In general, waste plastics have:

- a high H/C ratio (typically higher than coal). Injecting plastics increases the amount of H₂ within the BF and in the offgas exiting the furnace. An increase in the bosh gas H₂ content decreases bosh gas density, and therefore reduces the pressure drop or allows a greater gas flow for the same pressure. Since reduction by H₂ is less endothermic than direct reduction (*see* Section 2.1), there is a decrease in the energy requirements. 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 faster reduction rates, particularly at lower temperatures. The optimum RAFT is also lower because of the higher H₂ content in the raceway (*see* Section 5.2.2). However, a higher H₂ concentration in the shaft can lead to increased amounts of coke fines in the furnace shaft, decreasing permeability;
- a high CV, in many cases larger than coal. PE typically has a CV of around 46 MJ/kg; PP 44 MJ/kg, PS

Table 6 Specification for trace elements in waste plastics (Buegler, 2009a)

Element	
Chlorine, %	<2
Sulphur, %	<0.5
Mercury, mg/kg	<0.5
Cadmium, mg/kg	<9
Lead, mg/kg	<250
Zinc, mg/kg	<1000
Copper, mg/kg	<1000
Arsenic, mg/kg	<5
Chromium, mg/kg	<500
Nickel, mg/kg	<500

Table 5 Chemical composition of waste plastics, coal and fuel oil (Janz and Weiss, 1996; Long and others, 2006; Sørnum and others, 2001)

	PE	PP	PS	PET	PVC	Waste plastics (packaging)	Pulverised coal	Fuel oil
Carbon, wt%	85.6	85.75	92.16	64.71	41.4	77.81	79.6	85.9
Hydrogen, wt%	14.21	14.15	7.63	3.89	5.3	11.99	4.32	10.5
Sulphur, wt%	–	–	–	–	0.03	0.9	0.97	2.23
Ash, wt%	0.19	0.1	0.21	0.17	0.4	4.9	9.03	0.05
Chlorine, wt%	–	–	–	–	47.7	1.4	0.2	0.04
Potassium, wt%	–	–	–	–	–	0.048	0.2656	0.001
Sodium, wt%	–	–	–	–	–	0.092	0.0816	0.001

40.5 MJ/kg, PET 23.5 MJ/kg and PVC 18.8 MJ/kg (although there are wide variations between rigid and flexible PVC) (Ida, 2006). The higher the CV, the greater the amount of heat supplied by the material, and hence the greater the reduction in coke consumption;

- low sulphur and alkaline contents (often lower than coal);
- low ash if there is no plastic filler (typically lower than coal but higher than fuel oil). Therefore little additional slag is produced. But injecting waste plastics has led to an increase in the pressure drop (deterioration in the furnace permeability), which has been attributed to the ash component originating from the waste plastics. The high melting point (about 1750°C) of the ash means that it does not easily form slag (Asanuma and others, 2009);
- high chlorine content if PVC is present. Nearly all of the chlorine leaves the BF as hydrochloric acid (HCl), which can corrode the pipelines through which the offgas flows. PVC is typically removed from the waste plastic although dechlorination processes have been developed (*see* Section 4.2). Chlorine content at the Stahlwerke Bremen furnace is limited to below 1.5%, that is, about 3% PVC (Tukker and others, 1999). Concern has been expressed about the possible formation of dioxins and furans via the generated HCl, but measurements in the offgas have shown low contents (*see* Section 8.2).

The strength and hardness of the waste plastics can be an issue. Low strength agglomerated plastics are easily broken during transport (which may lead to blockage problems) and combustion (lowering combustion efficiency – *see* Section 5.3.2). The use of waste plastics in BFs enables the additional recovery of ferrous materials present in the plastic-rich waste streams (Delgado and others, 2007).

Injecting 1 kg of waste plastics replaced about 1.3 kg of pulverised coal in the BFs of JFE Steel, Japan, and about 1 kg of heavy oil at Stahlwerke Bremen, Germany (Li and others, 2007). Substitution of coke by WPI is limited to around 30%, although values of 40% (Ogaki and others, 2001) have been quoted. BFs need a consistent injectant quality for stable operation. The preparation of waste plastics, ASR and coal is the subject of the following chapter.

4 Preparation and injection

The quality of the pulverised coal and waste plastics injectants is important not only in terms of their utilisation in the BF itself, but also in the preparation, handling and distribution of the materials to the furnace. Coal and waste plastics are prepared and transported in separate systems to the tuyeres. The injectant is prepared and conveyed to a storage hopper. It is then pneumatically transported through individual pipelines or via a distributor to the individual tuyeres. This chapter discusses the preparation of coal and wastes plastics, and their transport to the tuyeres and injection lances.

4.1 Coal preparation

Pulverised coal 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. Milling and distribution of the coal to the injection lances form one of the main operating costs of an ironmaking plant. 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 resultant particle size distribution of the pulverised coal affects its handleability in pneumatic transport equipment and, at high injection rates, its combustibility (see Section 5.3.1). An example of a PCI system is given in Figure 5; it was used at US Steel Canada's (formerly Stelco Inc) Hilton Works in Hamilton, ON, Canada. The performance and safety of pulverisers are discussed in the Clean Coal Centre report by Scott (1995).

Pulverisers grind coal to one of two size fractions:

- pulverised coal where around 70–80 wt% of the coal is under 75 μm and the rest is below 2 mm; and
 - granular coal which has a 2–3 mm top size and a limit of 2% of coal over 2 mm and 20–30% below 75 μm .
- Systems injecting this coal size are termed granular coal injection (GCI).

The coarser grind has the advantage of lower grinding and drying costs, and 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). This report

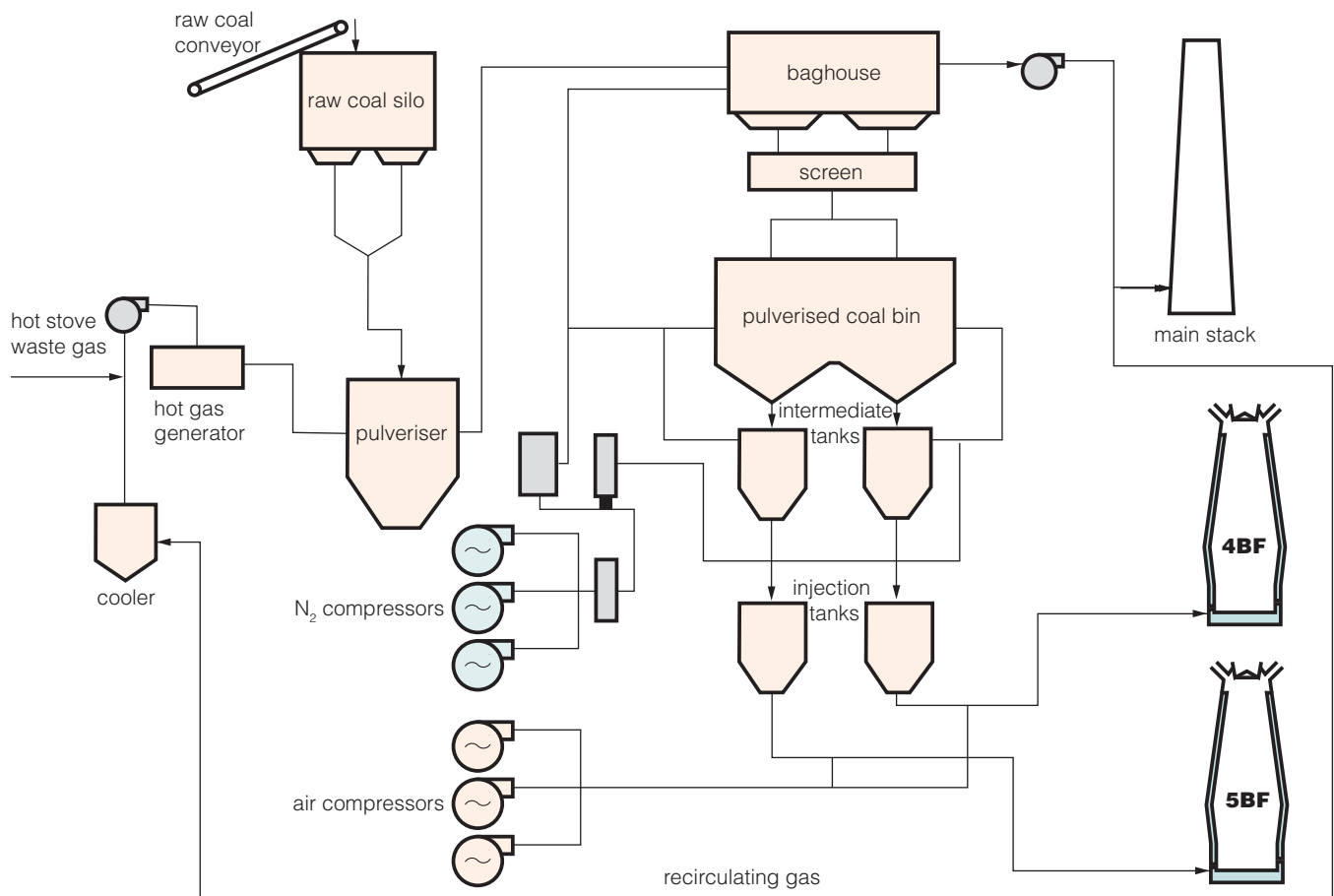


Figure 5 PCI system flowsheet (Hutchinson, 2001)

concentrates on the smaller size range (PCI) since this is the coal particle size typically utilised in BFs co-injecting waste plastics.

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

4.1.1 Drying

One of the functions of the pulveriser is to remove as much moisture from the coal as possible. Drying is necessary as moisture contributes to problems of free flow through the pneumatic transport systems and in the storage bins (*see* Section 4.3.2). Furthermore, moisture should be minimised since additional energy will be needed for its removal in the BF; injection of moisture increases the reductant rate. In addition, moisture affects both the energy consumption and output of the pulveriser, with higher moisture coals consuming more power and lowering the throughput. Evaporation of the coal surface moisture avoids agglomeration problems within the pulveriser; coals with high moisture and clay contents are particularly prone to sticking.

Typically, coals with a total moisture content of less than 10% (as sampled) are specified, contingent on the mill design. Bennett (2007) states that it is necessary to reduce the total moisture content of coal to around the equilibrium moisture level to reduce handling problems within the mill and storage bins. He quotes work by Brouwer and Toxopeus who suggest that the moisture content of coal leaving the mill should be two thirds the equilibrium moisture level. Equilibrium moisture varies with coal rank, maceral composition and ash content. The equilibrium moisture content of LV coals from Queensland, Australia is about 2%, and is around 6–9% in the HV coals from the Hunter Valley. Thus for coals with the same total moisture, the HV coals require less energy to dry the coal to a suitable moisture level than that required for a typical LV Queensland coal.

4.1.2 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 in order to lower operating costs. Wear affects pulveriser shutdowns and maintenance costs and so it is essential to evaluate whether the chosen coal/blend will cause excessive wear. Coal properties influencing wear include the mineral matter content and composition, particle size distribution, moisture, and bulk density. If a coal has a high moisture content then wear may be accelerated by the combined effects of wear and corrosion. The abrasive (hard) minerals in coal include quartz (SiO_2) and pyrite (FeS_2). As well as leading to wear of the grinding elements, the hard minerals can erode the pipes and ducts.

The most commonly used test for evaluating the abrasion

properties of coal is the Abrasion Index (AI), derived from the Yancey, Geer and Price (YGP) test. 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; coals with similar AI values can produce different wear rates. Other abrasion and erosion indices have been proposed, but are not yet widely accepted by the coal industry (Carpenter, 2002).

4.1.3 Power consumption and capacity

Reducing power consumption will lower mill operating costs. Mill power consumption and capacity (throughput) depends on the mill design, mill settings, the required fineness, and the properties of the coal. 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.

The principal coal properties influencing mill power consumption and capacity are:

- hardness, determined by the HGI (*see* Section 3.1.2). Generally, the higher the HGI, the easier the coal is to grind, with consequent lower power consumption and higher throughput of the coal. 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, 2005);
- maceral composition. In general, higher vitrinite coals tend to have lower grinding energy requirements than lower vitrinite coals since vitrinite is more easily ground than inertinite and liptinite (Carpenter, 1995). Bennett (2004, 2007) reports that the energy required for grinding vitrinite decreases with rank, whereas that for inertinite is almost rank independent. The effect of rank decreases above a reflectance of about 1.6 where the required breakage energy for vitrinite and inertinite are about the same.

Mill manufacturers provide charts 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. In addition, the HGI test does not simulate the actual grinding process taking place in a pulveriser (Carpenter, 1995, 2002).

4.1.4 Blends

Coals are commonly blended to optimise the relative strengths

of the constituent coals and produce a lower cost product. However, blends do not behave as an average of their components, but can be affected disproportionately by one coal with problem characteristics. 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). Preferential grinding of the softer macerals can also occur when milling blends. Coals containing swelling clays can absorb moisture after they leave the pulveriser and cool down. Even when present as a component of a blend, such coals can lead to blockages in the injection systems (Poultney, 2006).

4.2 Waste plastics preparation

Two of the most critical requirements for the successful use of plastics in BFs are their availability and processing costs. Plastics are utilised in a wide range of applications resulting in the widespread dispersion of plastic wastes. Waste streams include municipal wastes (such as wastes from households and restaurants), industrial wastes, ELV and WEEE. The wastes are often highly heterogeneous and frequently commingled with other materials. Consequently, the collection and sorting of wastes containing plastic residues is expensive. Some countries have subsidies to encourage the collection and recycling of wastes. In Germany, for example, the Duales System Deutschland (DSD) pays the consumers of recovered plastics to use this material (Wollny and others, 2001). Both Stahlwerke Bremen (now ArcelorMittal Bremen) and ThyssenKrupp Stahl were paid for taking waste plastics from DSD. This Section outlines the treatment of waste plastics after the initial pre-sorting and removal of other marketable streams.

The aim of the processing plant is to provide a feedstock of consistent quality with the requisite particle size and in sufficient quantity. The amount of processing required depends on the state in which the waste is received. Foreign materials such as metals and sand have to be removed as they can cause problems, including abrasion in injection systems and of the grinding elements in mills, and a lower hot metal quality. Additives added to certain plastic products during fabrication could also lead to abrasion problems. Small amounts of paper, stones and sand included with the plastics present no problems since they are discharged in the BF slag (Ogaki and others, 2001). Waste material contains many different types of plastic that may require sorting for separate treatment. This adds to the preparation costs. In addition, costs are influenced by the required particle size, which affects the combustion and gasification efficiency of waste plastics (*see* Section 5.3.2). Automation, where possible, can help to lower these costs.

JFE (as NKK) pioneered the recycling of waste plastics in BFs in Japan. Waste plastics separation and pretreatment plants have been built at both its East and West Japan Works to produce feed for the adjacent steelworks. These plants now have fully automated separation processes, thus avoiding

expensive hand sorting. Commercial injection of industrial waste plastics at JFE's Keihin Works (East Japan Works) began in October 1996. Typical wastes include office appliance equipment, bottles, containers, magnetic tapes and film sheets, but to begin with, excluded PVC (Wakimoto, 2001). The collected waste material is separated into two streams:

- solid plastic, which is shredded, the metal contaminants magnetically removed, and then crushed into 6–10 mm sized pieces; and
- film plastic which is cut into pieces, the PVC removed by centrifugal separation, and then melted and agglomerated by the use of the friction heat to form pellets with a particle size of 6–10 mm (Ogaki and others, 2001; Wakimoto, 2001).

In April 2000, WPI was expanded to include municipal wastes (*see* Table 4 on 16). The waste is treated in a similar manner (as solid and film plastic streams). JFE has now introduced a dechlorination step. The separated PVC pellets are heated with coke in a rotary furnace under a nitrogen atmosphere to 300–350°C, breaking them down into hydrocarbons and hydrochloric acid. The hydrocarbons are separated from the coke and injected into the BF (Asanuma and others, 2001; Hotta, 2003). The recovered hydrochloric acid is used in the steel plant pickling line. A similar scheme is used by Kobe Steel (*see* Figure 6); the separated light plastic stream is granulated and the heavy plastic chlorine-containing stream is dechlorinated before final granulation. The strength of agglomerated plastics, and their combustibility, can be improved by the addition of calcium carbonate (*see* Section 5.3.2).

A recycling plant for used electrical appliances (such as televisions and refrigerators) was constructed at JFE's East Japan Works and began operating in 2001. The recovered plastics are utilised as BF injectants. A PET bottles recycling plant with an annual capacity of 10,000 t has also been built at the works, commencing operation in April 2002 (Hotta, 2003). The PET bottles are processed to produce PET flakes, which can be utilised, for example, in the manufacture of textiles. Residues from the process, such as bottle caps and labels, are used as reductants in the BFs.

The latest addition at the East Japan Works is the construction of a waste plastics pulverisation plant (Advanced Plastics Recycling Process) in March 2007 (Asanuma and others, 2009). Here plastics are mixed, melted and dechlorinated. When cooled to room temperature, stresses are generated at the interfaces between the heterogeneous plastics, resulting in embrittlement. They are then crushed to produce 8000 t/y of pulverised plastics with a particle size of 0.2–0.4 mm. A higher combustion and gasification efficiency is achieved with a finer particle size.

In Europe, a process called Redop (REDuction of iron Ore in blast furnaces by Plastics from municipal wastes) has been developed. A slurry of the mixed plastic fraction (separated from municipal wastes) is heated in a stirred reactor at 230–300°C. The released hydrochloric acid is neutralised by the addition of a diluted water-soluble base. The dechlorinated plastics melt into droplets, the size of which are

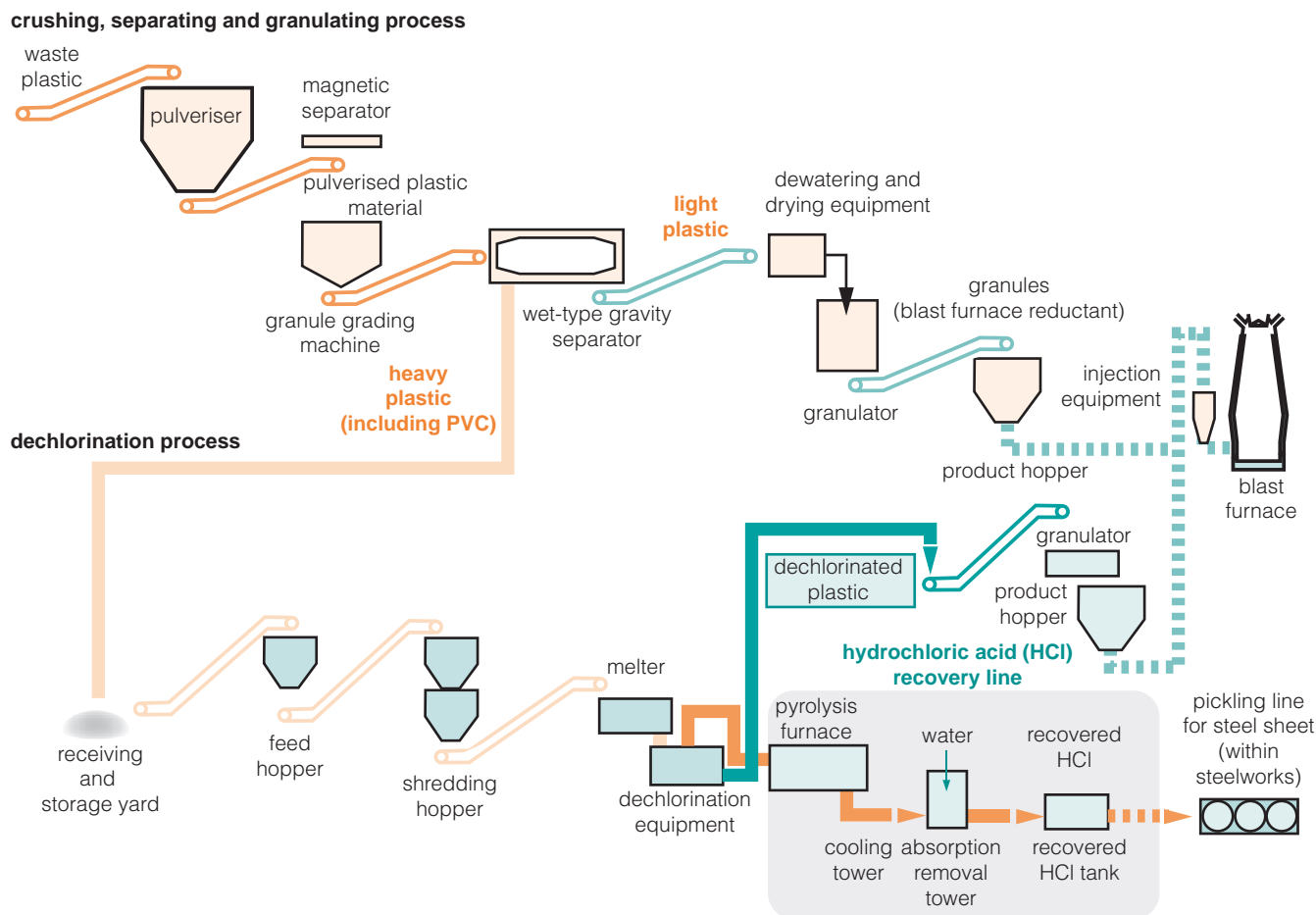


Figure 6 Flow diagram of the waste treatment process (Kobe Steel, 2007)

determined by the stirring and by the traces of the cellulose still present. Upon cooling, the plastic droplets solidify into granules (<0.15 wt% chlorine) suitable for injection into BFs. One tonne of Redop pellets was successfully injected at one of Corus's BFs in IJmuiden, Netherlands, in November 2004 (Vinyl 2010, 2005). The project was discontinued in 2006 for economic and market reasons.

Processes have been developed for the recovery of plastics from ELV. Recycling is complicated because the material is very heterogeneous, density and moisture content change from site to site and from day to day as different types of automobiles are shredded (Menad, 2007). After removing all possible recycling pieces and components such as batteries, lubricants, fuel and catalytic converters from the vehicle, the remaining hulk is sent to a shredder. Mechanical and magnetic separation processes are used to produce separated streams of ferrous metals, non-ferrous metals and waste (ASR, also known as fluff).

ASR is a heterogenous mixture consisting of plastics, rubber, wood, glass, oil, residual metals and dirt. According to Mirabile and others (2002), it can contain over 40% plastics, 21% elastomers, 10% textiles, 16% glass, 5% paint and protective coatings, 3% ceramic and electric materials, and 4% of other materials. The ASR composition strongly depends on the make, model and registration year of the vehicle, with the plastics content increasing over the years. ASR from an Italian shredding plant had a VM and ash

contents of 54.2% and 36.2%, respectively (higher than coal), and a CV of 16.7 MJ/kg (Mirabile and others, 2002). Small amounts of ASR can be injected into BFs without treatment (Menad, 2007), but larger quantities can cause problems. For instance the non-ferrous content (such as zinc, copper and lead) may adversely affect the hot metal quality, which is difficult to rectify at a later point. The chlorine content can also cause corrosion problems in the offgas cleaning equipment. Therefore the ASR is treated to remove detrimental materials.

A number of initiatives have been undertaken to treat ASR for recycling purposes. Most of these are based on isolating relatively pure materials from ASR by exploiting property differences, such as density or solubility in different solvents. Jody and Daniels (2006) review some of these processes. The Volkswagen-SiCon (VW-SiCon) process, which has been implemented at various locations in Europe, produces several fractions from ASR, two of them originating from plastics (see Figure 7). The process uses a combination of mechanical operations to separate the ASR according to its optical characteristics and physical properties, such as density, particle shape, magnetic properties, and conductivity. The shredder 'granules' fraction (a mixture of hard plastics, low in PVC) can be used in BFs. SiCon GmbH supplies low chlorine shredder granules, produced in the Antwerp, Belgium plant, to Salzgitter Flachstahl for injection into its BF C (SiCon, 2008). The shredder fibre fraction can be densified to serve as a reducing agent in BFs or replace coal in coke ovens and

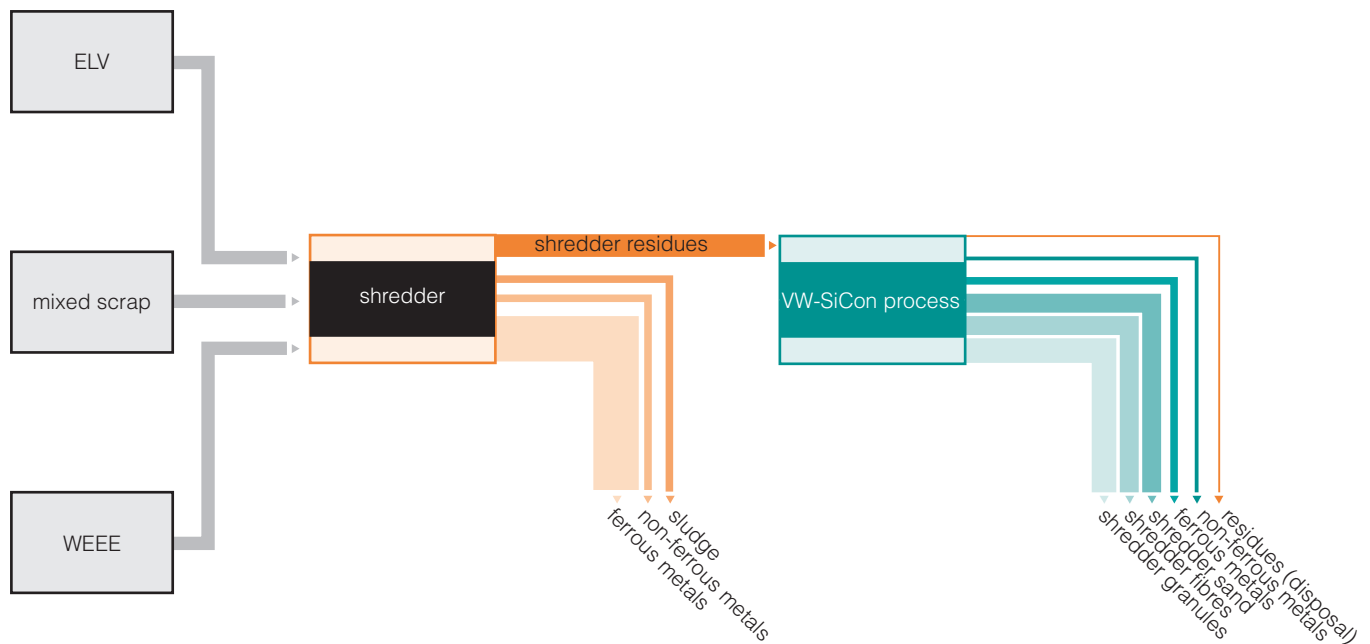


Figure 7 Flowsheet of the VW-SiCon process (SiCon, 2009)

power plants (Fischer, 2006). The process can also treat mixed and electronic (WEEE) scrap. More information about the process can be found on the website www.sicontechnology.com.

TBS (Technische Behandlungssysteme) in Austria mechanically sorts ASR into various fractions. The plastic granules (<10 mm) are supplied to voestalpine Stahl's BF A (Mitterbauer and Buegler, 2009).

The Thermo-bath process developed by JFE Steel uses a coal tar based oil, a by-product of the steelworks, to separate ASR into floats and sediments (metals, glass and sand) by specific gravity differences. The bath is heated to 280–300°C which melts the PVC and polyurethane resins and, at the same time, dechlorinates the PVC. A 1200 t/y pilot plant was built at the East Japan Works. The separated floats contained 92% organic material (mostly plastics) and 8% inorganics (with less than 0.01% copper); over 70% of the chlorine was removed. No problems were encountered in a 2 h test injection of the recovered floats in a commercial BF. The recovered metals can be used in the steel making process or as a raw material for non-ferrous metals. Calculations indicated that 73% of the ASR (15% of ELV) can be used as BF reducing agents and 5% of ASR (1% of ELV) can be recovered as valuable metals. A total recycling rate of about 96% for ELVs could be achieved (Takaoka and others, 2003). The process can also treat shredder dust from electrical appliances (Hotta, 2003).

4.3 Injection system

The injection system pneumatically transports and meters the reductant 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 lances inject the reductant in equal amounts through the tuyeres, which are arranged symmetrically around the circumference of the BF. A critical factor in the distribution system design is to ensure uniform

feed of reductant to each tuyere without fluctuations in the reductant delivery route. Any interruption in injectant supply can quickly lead to serious problems – the higher the injection rate, the more serious the consequences of an unplanned interruption.

Coal and waste plastics can be transported:

- through completely separate injection systems and lances;
- through separate injection systems to a common lance;
- as a blend.

In most cases coal and waste plastics are transported separately because of their different particle sizes (coal is pulverised whilst waste plastics are in the 1–10 mm size range) and densities. In addition, the required handling characteristics of the coal will vary because of differences in the design of coal preparation and injection systems. This will also be the case for waste plastics. JFE Steel is now injecting coal/waste plastic blends at one of their BFs. The materials, though, are still transported separately and mixed in the piping just before the injection lance (*see* Section 5.3.2).

4.3.1 Injection vessels arrangement

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

- serial arrangement where the upper vessel periodically replenishes the lower one, which is always kept under pressure, and injects the reductant continuously into the BF (*see* Figure 8). This arrangement is used at Stahlwerke Bremen (Janz and Weiss, 1996), by ArcelorMittal Eisenhüttenstadt (Buchwalder and others, 2003) and by voestalpine Stahl for injecting plastics; and
- parallel arrangement where the two vessels inject alternately (*see* Figure 5 on page 20). An overlapping operation is required to maintain reductant injection during the change over period.

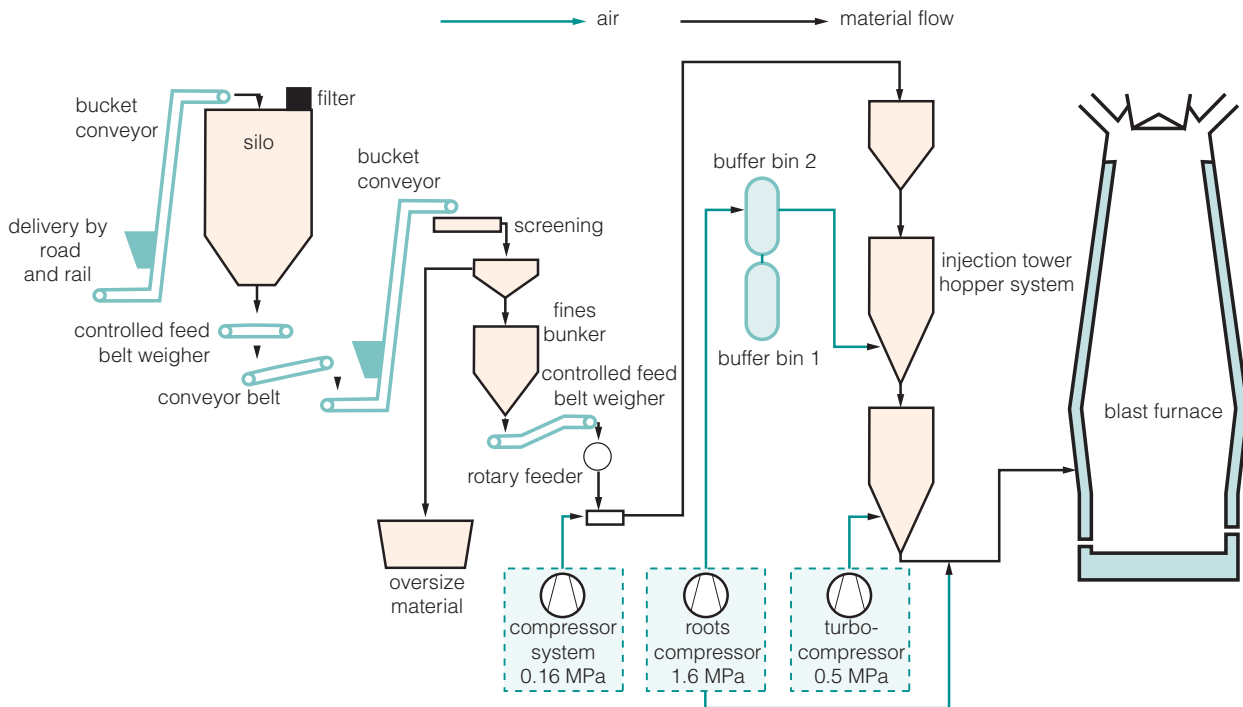


Figure 8 WPI system flowsheet (Mitterbauer and Buegler, 2009)

It is important to control the amount of reductant injected. Therefore the injectant vessels are continuously weighed and the flow rate of the reductant is carefully controlled.

Handling problems of pulverised coal in the storage bins that feed the injection vessels and pipelines have been related to the amounts of moisture and ultrafine particles, and the presence of clays in the product (discussed in the following section). Fouling of the bins by plastic fluff has also been reported (Wakimoto, 2001). External heaters and/or insulation may be required to reduce the likelihood of bin blockages in colder climates where condensation may occur on the inside of the bin walls. At the Hilton Works in Canada, nitrogen was blown through aeration pads in the bottom of the intermediate injection tank (*see* Figure 5 on page 20) to ensure free flowing when pulverised coal is transferred to the lower injection tank (Hyde and others, 1996).

4.3.2 Conveying line

Coal and waste plastics from the injection vessels can be transported by:

- individual pipes to each tuyere. The amount of reductant is independently controlled and charged in each pipe (*see* Figure 9);
- a common pipeline to a distributor adjacent to the BF. The distributor then equally divides the reductant into the individual pipes leading to each tuyere. An advantage with this system is that the distance between the preparation plant and BF can be longer than with the individual pipe system.

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



Figure 9 Pressure hopper with distributors (32 in total) (Buegler, 2009b)

Depending on the ratio of reductant to conveying gas, the reductant is pneumatically transported from the injection

vessel to the tuyeres in either:

- dilute phase; or
- dense phase.

The transport gas loading in dilute phase systems for coal 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 (Carpenter, 2006). The carrier gas for plastics is usually compressed air. Gas velocity for waste plastics in dense phase systems is 3–8 m/s (Snowdon, 2008). ArcelorMittal Eisenhüttenstadt utilised dilute phase conveying for the plastic pellets (up to 10 mm) and dense phase conveying for the pulverised coal (Buchwalder and others, 2003).

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, and these variables interact with each other. The low velocity in dense phase systems means low pipeline and component wear, whereas the high transport speed of dilute phase systems can lead to wear, particularly at pipe bends. The wear rate is determined by the hardness, shape and velocity of the particles. Plastic agglomerates have an irregular particle shape that could cause erosion, whereas extruded plastic pellets have a regular shape. Crushed plastic particles are harder than the agglomerated pellets (Asanuma and others, 2000). Coal properties influencing wear are discussed in Section 4.1.2. Lining the parts of the pipes prone to erosion with, for example, a urethane elastomer material will provide abrasion resistance, as well as retarding the build-up of fines that can lead to blockages.

Coal and waste plastic properties that have been related to transfer line blockages are:

- moisture content. High moisture coals and blends can be problematic. Thus strict moisture limits on the milled coals are applied. The moisture content of waste plastics is also controlled to prevent blockages;
- clay minerals in coal. The presence of clays, which swell in the presence of water, may cause problems, especially if there is a pressure drop in the transport system; and/or
- the presence of ultrafine particles.

As the fines content (<5.8 µm) of the pulverised coal 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 buildup of these deposits at bends in the pipes were 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 (Hutchinson,

2001; Hyde and others, 1996). In addition, preferential grinding of the softer coal in a coal blend (*see* Section 4.1.4) could lead to a high proportion of ultrafine particles, resulting in blockages.

The particle size distribution of agglomerated mixed plastics is also important. The proportion of particles below 250 µm is limited to 1% (Buchwalder and others, 2003). The particle size specification in this case was 0–10 mm and the granules were conveyed in a dilute phase. The authors also report that stable injection requires about 50% of the injected plastics to have an upper particle size of 6 mm. The use of fibrous plastic particles is difficult because the fibres agglomerate to form larger particles blocking the pipes (Janz and Weiss, 1996). Plastic fluff can also clog the pipes (Wakimoto, 2001). Plastic particles can become electrostatically charged during their transport through pipelines causing them to adhere to the walls. In severe cases the pipes may block, especially at bends. The addition of a free-flowing fine grained material can militate the effect (Osing, 1997).

Coal-plastic blend are potentially an economic means to get finely ground plastics into the BF without the need for an expensive separate injection systems for the two materials. However this would increase the plastic preparation costs since they would need to be ground to around the same size of the pulverised coal. Pilot-scale tests on blends of 10% PE with 90% of HV or LV coals gave no problems in the pressurised screwfeeder dispensing system or pipelines despite differences in their particle size distribution and particle shapes. The nominal particle size for the coals was 80% <90 µm and the PE had a top size of 600 µm. The majority of shredded PE grains were elongate-tabular to lath-like and up to 1.2 mm long. However, mixtures of pulverised coal with up to 30% of thermally agglomerated plastics (particle size <2 mm) have blocked pipes, dosing and distribution devices due to separation and aggregation on the plastics. It was apparently caused by high fractions of non-granular rather than fibrous and fluffy plastics particles in the blend (Probst, 1999).

Blockages can be alleviated by improvements in the pipe layout and distribution systems and, in some cases, by adjusting the preparation system (such as the coal pulveriser) to produce a coarser particle size. All injection systems have procedures for detecting and clearing blockages since it is a common phenomena. Transfer lines include purge ports where blockages are cleared, typically with high pressure air.

A simple and practical test is needed to assess the flowability and handleability of pulverised coals and their blends, and waste plastics. This would enable problematic materials to be identified before they are utilised. Some of the available methods, such as the Jenke shear cell, Johanson indicizer and Edinburgh cohesion tester, are discussed in Carpenter (2002, 2006).

4.3.3 Injection lances

The injection lance injects coal and/or waste plastics into the blowpipe which leads up to the tuyere (*see* Figure 10). The

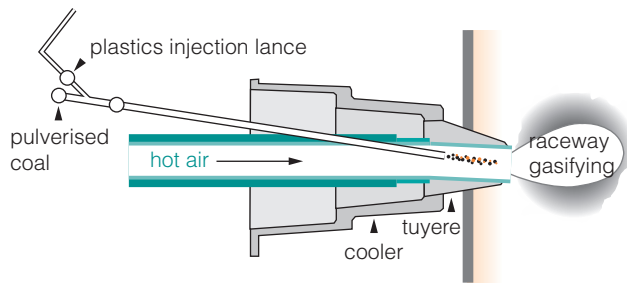


Figure 10 Schematic of a BF tuyere (Ogaki and others, 2001)

particles are immediately heated by the hot blast, ignite, gasify and burn. The design and placement of the lance influences the combustion efficiency of the reductant. Originally the lances were straight steel lances that were positioned at or close to the tuyere/blowpipe interface. Designs incorporating the injection of oxygen directly into the flow of the coal particles (oxy-coal lances) and/or ways of generating more turbulence at the lance tip have been developed to improve combustion efficiency. These include coaxial lances (where the reductant is injected through the inner pipe and oxygen through the surrounding annulus), high dispersive lances, bevelled lances, slit lances, eccentric (non-concentric) double lances and swirl lances. Preheating the coal to increase combustion efficiency is also practised.

Problems that occurred when coal and waste plastics injection were first introduced, such as lance and tuyere blockages and melting of the lance tip, have largely been mitigated. Blockages are mostly due to the coal and waste plastics being heated to a temperature where they become sticky and adhere to the surface of the injection lances and tuyeres. Ash deposition can be minimised by utilising coal with a high AFT (*see* Section 3.1.2). For all practical purposes, the AFT should be 50°C higher than the hot blast temperature. Lances can also plug if coals with a high fluidity cake near the tuyere tip. This can be overcome by avoiding coals with high caking indices, or by increasing the flow rate (Kruse and others, 2003).

Positioning the injection lance closer to the tuyere has reduced the extent of ash impingement in the blowpipe. Utilising air-cooled coaxial lances has helped prevent clogging and erosion, and can prolong the life of the tip. The flow rate of the cooling air should be minimised to abate its cooling effect on reductant combustion (*see* Chapter 5). Nevertheless, clogging of lances can still be a frequent occurrence. There are set procedures for detecting and clearing these blockages before they can cause any problems. Utilising different alloys for the injection lances and limiting the hot blast temperature has also militated melting of the lance tip. The durability of a lance is an important operational consideration as these burn up over time.

Raceways are vital regions of the BF even though their total volume usually does not exceed 1% of the inner furnace volume. They supply the process with heat and reducing agents. Injection of auxiliary fuels inevitably affects raceway conditions which, in turn, have consequences outside the raceway (*see* Figure 2 on page 9). Unburnt particles exiting the raceway can cause operational problems such as reduced permeability, undesirable gas and temperature distributions, excessive coke erosion, and an increase in char carryover. The amount of unburnt char increases with increasing injection rates. Consequently the combustion and gasification behaviour of the injected fuels in the raceway is an important factor for stable furnace operation. This chapter discusses the combustion behaviour of coal and waste plastics and how their combustion efficiency could be improved. It has become apparent that furnaces can consume more injected coal and waste plastics than that combusted within the raceway – the unburnt material is consumed elsewhere in the furnace (*see* Chapter 6).

Coal combustion within BFs has been extensively studied (reviewed in Carpenter, 2006), as has the combustion of waste plastics, but fewer studies have been carried out on the injection of coal with waste plastics or ASR. The studies have been conducted using bench-scale equipment such as thermal gravimetric analysis (TGA), drop tube furnaces (DTFs) and wire mesh reactors (WMRs). These techniques do not fully simulate conditions within the raceway. The residence time of pulverised coal particles in a DTF, for example, is of the order of seconds whereas it is around milliseconds in an industrial BF raceway. Therefore these techniques are typically used to provide a comparative evaluation of the materials. Coal combustion studies using TGA, DTFs and WMRs, and their limitations, are reviewed by Carpenter (2002), albeit in relation to power plants. The application of these techniques in studying coal combustion in BFs is covered in Carpenter (2006).

Another approach is the use of specially designed facilities to simulate raceway conditions. These include the injection of a hot blast into a packed coke bed, often termed ‘hot model’. These have the ability to simulate combustion conditions for short residence times of milliseconds, as well as different raceway locations. However, the pilot-scale facilities still do not fully simulate raceway conditions in industrial BFs. For example, due to costs, they may not work at pressures close to the tuyere/bustle main pressure. Higher pressures in the raceway increase the injectant gasification rate.

A number of computer models are available for assessing the behaviour of the injectant in the raceway and elsewhere in the BF. These include those by Jordan and others (2008), Maldonado and others (2008) and Tian and others (2008). The validity of these models have been questioned because the mechanisms they are portraying are complex and not fully understood. Their accuracy is dependent on the assumptions made and the validity of relationships built into the models. Since the behaviour of the injectant is strongly influenced by

BF design and operating conditions, as well as the injectant properties, the models are probably only applicable for the particular BF, operating conditions and the same types of injectants on which they were developed and tested.

The limitations of all these techniques should be borne in mind in the following discussion of the combustion and gasification behaviour of pulverised coal, waste plastics and ASR.

5.1 Combustion process

Combustion of coal and waste plastics 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 (1400–2200°C), elevated pressures (around 0.3–0.6 MPa) and short residence times (10–40 ms for pulverised particles). It is under these severe conditions that a high level of injectant combustion needs to be achieved.

The combustion process for coal can be divided into the following steps, some of which are overlapping:

- heating. The injected pulverised particles (<75 µm) are rapidly heated as they enter the oxygen-enriched hot air blast. The heating rate is determined by the operational conditions but is around 10⁵–10⁶ °C/s. The hot blast temperature is typically 1000–1200°C and the gas velocity is about 180–250 m/s;
- pyrolysis of the particles to produce noncondensable volatiles (gases), condensable volatiles (tars) and a carbonaceous char. It takes about 2–20 ms to complete devolatilisation;
- ignition and combustion of the volatiles to produce principally CO₂ and H₂O. This takes a few milliseconds;
- partial combustion of the residual char by oxygen. Char combustion 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;
- 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 combustion of plastics follows a similar path to coal except that some types of plastic thermally decompose into a combustible liquid and volatile gas (*see* Section 5.2.2). Less char is formed from those plastics that have a lower ash content than coal. Therefore gas combustion can be more important than char combustion. Plastic particles have a low thermal conductivity and hence heat transfer in the raceway is high. Combustion behaviour is dependent on the type of

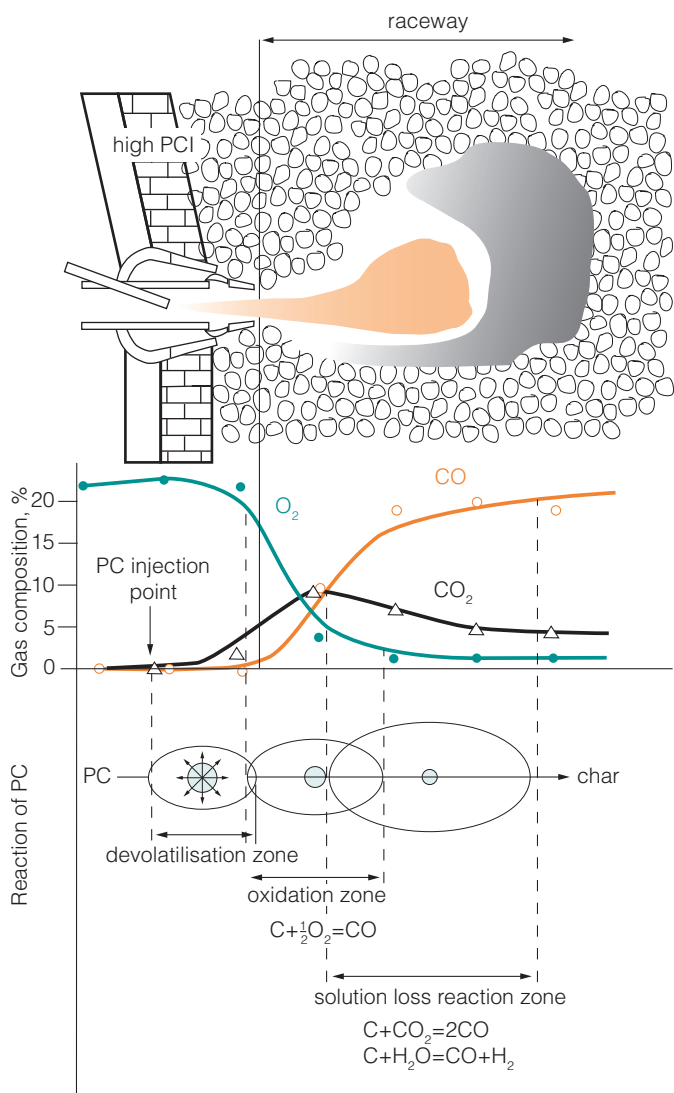


Figure 11 Pulverised coal reactions in the raceway (Kamijou and Shimizu, 2000)

plastic, its properties (such as hardness/density) and size (see Section 5.3.2). Larger particles have a longer residence time in the raceway – around 4–6 s for 7 mm sized particles (Jordan and others, 2008).

It is the combustion characteristics of coal and waste plastics rather than coke combustion that govern the gas composition and temperature distribution in the raceway since they are preferentially combusted. Figure 11 illustrates some of the coal combustion steps occurring within the raceway at the Kakogawa BF1 in Japan, and how the gas composition varies. Most of the oxygen is consumed near the tuyere nose, whilst a CO₂-rich atmosphere is produced in the middle, and a CO-rich atmosphere at the end of the raceway. Figure 12 shows how the gas composition (including H₂) varies in a simulated (hot model) raceway when waste plastics are injected. For comparison, the Figure includes the gas composition for PCI, and for all coke operation when only blowing hot air through the tuyere.

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

- properties of the coal, waste plastics and ASR, such as

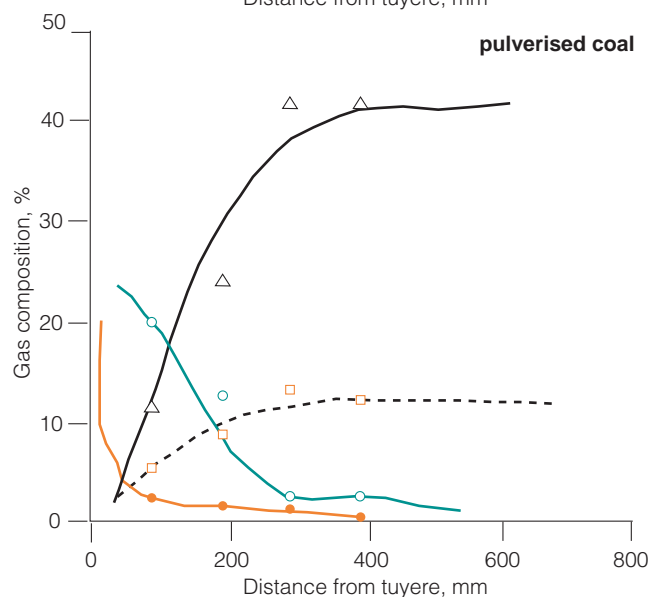
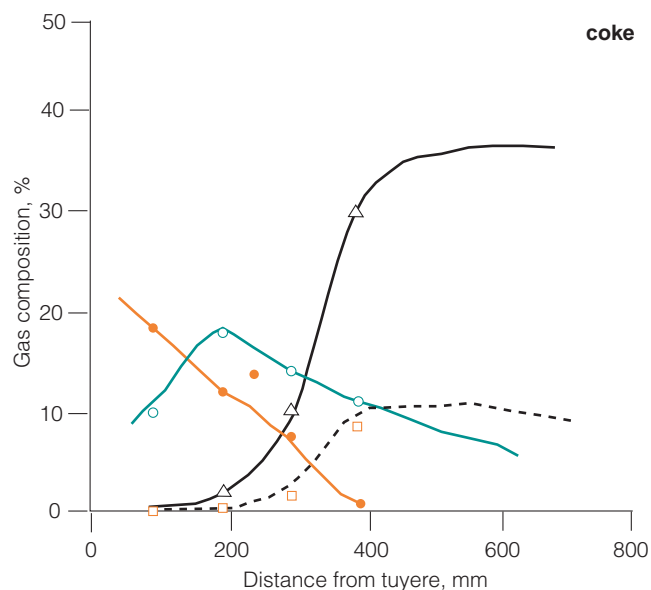
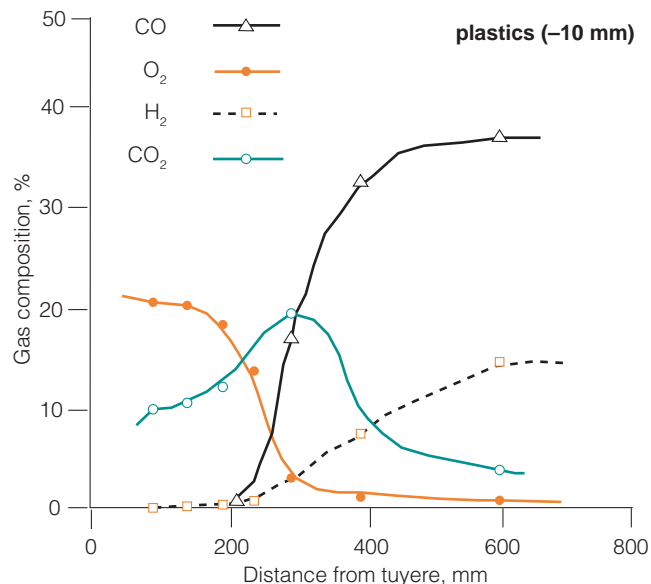


Figure 12 Gas composition in simulated raceway (Wakimoto, 2001)

- the volatile matter content, particle size and density; and
- operating conditions, for example, blast gas composition and temperature, and lance position and design.

5.2 Effect of coal rank and plastic types

The combustion and gasification behaviour of pulverised coal and waste plastics in the raceway is influenced by their properties. This section outlines the effect of their properties, in general terms, on the flame temperature and combustion efficiency. An earlier report by Carpenter (2006) covers the combustion and gasification of coal in more detail. The influence of particle size and operating conditions on the combustion and gasification behaviour of the injectants is examined in Section 5.3.

5.2.1 Coal

PCI has a cooling effect on the flame temperature. The flame temperature is an important parameter as it 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 theoretical flame temperature. RAFT calculations can vary from one company to another depending on the assumptions made, and so values may not be directly comparable. There is an optimum RAFT for each furnace depending on factors such as the burden composition and permeability, coke quality, and blowing rate.

Injecting coal lowers the RAFT (compared to all-coke operation) as it promotes endothermic reactions. Table 3 on page 13 shows how RAFT changes with coal rank. 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). In general, the higher the H/C ratio in the fuel, the greater the cooling effect. The RAFT also decreases with increasing injectant rate. Increasing the blast temperature and/or oxygen enrichment, and/or decreasing blast moisture can compensate for the cooling effect of coal (see Section 5.4).

Combustion experiments under conditions simulating the BF environment have indicated that combustion efficiency generally increases with increasing coal VM (Borrego and others, 2008; Carpenter, 2006). HV coals are easily gasified, producing a larger quantity of gas, with a lower calorific value, and a smaller amount of char compared to low and mid volatile coals. Consequently, gas combustion is more important for the lower rank coals than char combustion (Toxopeus and others, 2002). If gas combustion is incomplete, soot can be formed, and this could lead to a deterioration in furnace permeability when it leaves the raceway. Soot has a lower reactivity than unburnt char (Chen and others, 2007). The extent of devolatilisation is influenced by the coal particle size, with finer sizes leading to more complete devolatilisation (see Section 5.3.1).

As the coal VM content decreases, the ultimate combustion efficiency is governed by the char reactions since ignition and combustion of the VM is rapid. Chars with a higher reactivity

have a higher combustion efficiency. However, it has been argued that 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. Others have argued that in view of the small particle sizes used (more than 80% <75 µm in PCI) 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 (see Carpenter, 2006). Char reactivity is certainly important outside the raceway. Under the conditions in the upper furnace, char gasification is likely to be controlled by the rate of chemical reaction. Therefore, the overall char gasification reaction rate is likely to be influenced by the chemical reactivity of char to CO₂.

In general, char reactivity increases with coal volatile content (Carpenter, 2006), that is, HV coals typically produce more reactive chars than LV coals, and hence a better burnout. There are exceptions as the reactivity of char is influenced by a number of factors including:

- its morphology (surface area, porosity);
- its resultant structure;
- its composition; and
- the operating conditions.

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. Char fragmentation, which is influenced by its structure, increases the external surface area. 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), and hence have a higher char reaction rate. Fragmentation may be one of the reasons why some workers found that the volatile matter has little effect on the combustibility of coals (Bennett, 2007).

Chars formed from higher rank (LV) coals at high temperatures are generally more ordered and hence less reactive (Lu and others, 2001, 2002). 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.

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). Kalkreuth and others (2005) found that although inertinite-rich subbituminous coal chars were

intrinsically less reactive than the vitrinite-rich ones at 500°C, this was no longer relevant at high temperatures (1300°C). It is likely that differences in the combustibility of coals would be greatly reduced under the very intense combustion conditions in the raceway.

The combustion performance of coals can be enhanced due to catalytic effects of the constituent minerals or retarded by excessive mineral concentration. 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, 2006). 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.

Although coals and chars with a high reactivity are generally preferred, too high a reactivity can lead to unstable furnace conditions. Test injections of a HV coal at a rate of 150 kg/thm at the Gary Works BF14 in the USA resulted in higher and more variable blast pressure, more erratic stockline control, lower gas utilisation and higher offgas temperatures. This instability has initially been attributed to the high reactivity of the coal (and its char) causing it to burn too quickly; investigations are still ongoing (Lherbier and Serrano, 2009).

Coal blends

Blending can dilute the unfavourable combustion properties of a coal. But the combustion performance of a blend is more complex than that of a single coal. Each of the coal components devolatilises and combusts at different temperatures and at different times, and their burnout could therefore vary considerably. In addition, interactions between the component coals can occur, complicating predictions of the blend's combustion behaviour. Injecting waste plastic as well, further complicates the matter since it can also interact with the coal and competes for oxygen.

Interactions first occur in the milling plant (*see* Section 4.1.4) where there is the potential for large differences in the size distribution of the component coals, especially if there are significant differences in the hardness of each coal. Disproportionation also occurs, influencing the mineral and petrographic composition of the resultant particles, and the subsequent combustion behaviour.

Interactions between the component coals can enhance combustibility of the blend. For example, the combustibility of LV coals can be enhanced by blending with HV coals (Carpenter, 2006; Shen and others, 2009). The HV coal releases more VM helping to form a higher gas temperature field, which then heats up the LV coal. This promotes its devolatilisation, ignition and combustion. The synergistic effect is more pronounced the higher the fraction of HV coal, up to a certain percentage. A blend consisting of about 70% HV coal (32.5% VM) and 30% LV (20% VM) gave the

highest burnout under simulated BF conditions (Shen and others, 2009).

TGA investigations under a CO₂ atmosphere by Osório and coworkers (Gomes and others, 2006; Osório and others, 2006) on blends comprising of 25–75% Brazilian subbituminous coal (33% VM, db) with LV coal (15% VM, db) found that the reactivity to CO₂ was additive, implying there were no interactions between the coals. But when a reactivity index based on the conversion time of 50% of the subbituminous coal was employed, the reactivity of the blends was non-additive. This suggests that there were interactions between the coals, with the addition of LV coal reducing the subbituminous coal's reactivity.

5.2.2 Waste plastics

Plastic types vary in composition, structure and degree of order (crystallinity). For instance, the structures of PP, PS and PVC differ from that of PE as these contain methyl, benzene and chlorine, respectively, as the repeating unit. PE consists of a long chain of aliphatic hydrocarbons made from ethylene monomer. Both HDPE and LDPE essentially have a similar molecular structure except the chain branching which is responsible for the density differences (Sørum and others, 2001). Consequently, the thermal decomposition behaviour of the various waste plastic constituents differ. Thermal decomposition of PE, for example, favours greater H₂ release compared to CO. Differences in the chemical structure of the waste plastic constituents also have implications on their combustion behaviour when mixed or co-injected with coal.

Injecting plastics and/or ASR lower the RAFT as they promote endothermic reactions. WPI has a stronger cooling effect than PCI (*see* Figure 13), and the effect is dependent on the type of plastic. Polybutylene terephthalate (PBT) has a higher cooling effect than PE which, in turn, is larger than PS (Heo and others, 2000a; Janz and Weiss, 1996). Mirabile and others (2002) found that the raceway temperature decreases from 1832°C when using 100% coal, to 1830, 1720 and 1718°C when the coal was replaced by 0.1, 1 and 10% of ASR (fluff), respectively. The coal and ASR mixtures were injected into a hot coke bed (hot model). Injection rates of 100 kg for low grade plastics and up to 170 kg for PS are theoretically possible under constant tuyere conditions without incurring a flame temperature drop to below 2000°C (Lüngen and Theobald, 1997). Increasing the blast temperature and/or oxygen enrichment, and/or decreasing blast moisture can compensate for the cooling effect of the injectants (*see* Section 5.4).

TGA studies have shown that the pyrolysis behaviour of PS, PP, PBT, LDPE and HDPE are similar, with a rapid weight loss of hydrocarbons occurring within a narrow temperature range of around 80–100°C (Heo and others, 2000a; Sørum and others, 2001). The pyrolysis of PS began and finished before PP which, in turn, began and finished before PE (Cao and others, 2005). The thermal degradation behaviour of PVC is more complex. First benzene and then chlorine are released, followed by degradation of the remaining hydrocarbons (which occurred at a similar temperature to the other plastics).

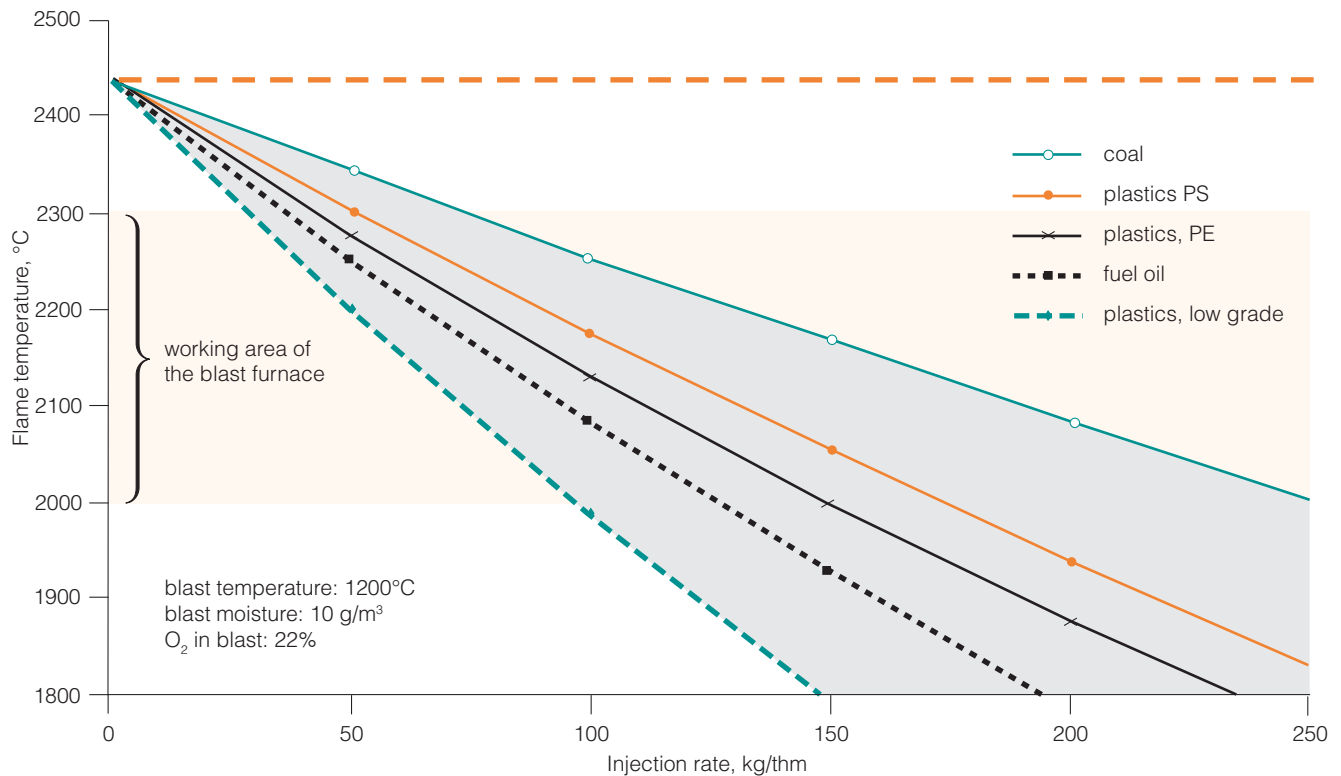


Figure 13 Effect of various injectants on the flame temperature (Janz and Weiss, 1996)

Additionally, PVC produced a char fraction, unlike the other tested plastics. It has a more complex structure. In general, PE (and some other types of plastics) thermally decomposes into a combustible liquid and volatile gas (Cao and others, 2005; Kim and others, 2002).

Zevenhoven and others (1997) also found that PVC produced a char unlike LDPE, HDPE, PP and PS (without a colour agent) when combusted in an electric furnace at 750–950°C. The ashes produced from coloured PP and PS were directly related to the colour agent. Although uncoloured PS yielded no solid residue after pyrolysis, it did generate a large amount of soot. Panagiotou and Levendis (1994) report that PVC produced a lot of soot when combusted in a DTF at 927–1227°C, followed, in order, by PS, PP and PE. PVC showed a faster ignition and shorter pyrolysis and combustion times than similarly sized PE, PP and PS (Panagiotou and Levendis, 1994; Zevenhoven and others, 1997). The faster ignition was attributed by the latter authors to the lower ‘activation energy for thermal degradation’ of PVC (85–140 kJ/mol for PVC compared to 200–300 kJ/mol for the other plastics).

Differences in the pyrolysis behaviour between the various plastics is also due to differences in their chemical structure which can alter their reactivity. The reactivity of PS was greater than the reactivity of PP which, in turn, was higher than LDPE and HDPE (Sørum and others, 2001).

5.3 Particle size effects

The combustion performance of coal and waste plastics is influenced by their particle size. For complete conversion, and thus effective utilisation of the injected materials, the heating up, devolatilisation, pyrolysis and combustion of the particles

need to take place in the period between their entry into the hot blast and the raceway boundary.

5.3.1 Coal

Generally, higher amounts of VM are released with decreasing coal particle size (Carpenter, 2006). This can facilitate gas phase combustion. Finer particles have higher specific surface areas and hence higher heating rates. The granular coals tested by Hutny and others (1996) released lower amounts of VM than when pulverised. Calculated pyrolysis yields indicated that nearly all the VM from the pulverised coals was released whereas it was incomplete from the granular coals. The presence of residual VM in the granular coals affects the subsequent CO₂ gasification reactivity of the chars (*see* Section 6.1). Chen and others (2007) report that the extent of devolatilisation in the finer particles (45–75 μm) was more complete than the larger 75–150 μm ones. The effect was more pronounced for the LV bituminous coal (14.7 wt% VM) compared to the HV bituminous coal (37.3 wt% VM). They found that a higher VM release can result in more soot and tar production, produced from secondary reactions of the volatiles. The reactivity of the soot was lower than that of the unburned char. Consequently, the lower the soot formation, the better the blast furnace stability.

The combustion efficiency (or burnout) of coal generally increases with decreasing particle size since a higher surface area is available for reaction (Carpenter, 2006). Larger particles require a longer time for burnout. The increase became more pronounced as VM content increased for coals with 20, 26.9 and 32.1% VM, db (Mathieson and others, 2005). However, the particle size effect is also dependent on

oxygen stoichiometry, as well as coal rank (and char reactivity – see Section 5.2.1). Vamvuka and others (1996) found that larger particles of bituminous coal (30 wt% VM) generally gave a higher combustion efficiency (degree of burnout) at O/C ratios >2 (fuel lean conditions) under simulated BF conditions. The smaller particles had a higher combustion efficiency under fuel rich conditions (O/C <2). On the other hand, the combustion efficiency of lignite (38.7% VM) generally increased with increasing particle size as well as with increasing O/C ratio. The particle sizes varied from 63 to 250 μm and the samples were blown with hot air into an induction furnace at 1500°C (residence time <20 ms). The authors attributed the behaviour to fragmentation of the larger particles into smaller pieces due to the thermal stresses induced by the higher temperature gradients inside them. The small particles formed allowed better diffusion of oxygen, thus aiding combustion. Interestingly, the degree of burnout and the O/C ratio (1.5–4.5) for the 63–90 μm lignite particles were nearly identical with that for the 150–200 μm bituminous coal particles.

5.3.2 Waste plastics and co-injection with coal

The combustion behaviour of the different plastic waste constituents will vary. PE is often used as a surrogate material for investigating WPI in a BF due to the abundance of its derivatives in waste plastics. The ignition temperature of PE increases with increasing particle size (360°C with 3–5 mm compared to 380°C with a 6–10 mm particle size) when combusted in air (Cao and others, 2005). This was attributed to the larger contact surface area of the finer particles to oxygen. Therefore finer plastic particles are expected to have a higher combustion efficiency than coarser ones (like coal). An analysis of the CO₂ concentration in the generated gas (often used as a measure of combustion efficiency) indicated that the larger PE particles would undergo combustion further away from the tuyeres, and therefore would take longer to combust in BFs than finer ones. This is a consequence of the low thermal conductivity of plastics (Cao and others, 2005; Kim and others, 2002).

Cao and others (2005) also found that, as well as having a lower ignition temperature, PE has a shorter burning time and higher burning rate compared to the studied coal (VM content not given) with a particle size of 0.6–0.7 mm. The reason given was that PE decomposes to combustible gas at high temperatures. The combustion of the pyrolysis gas with oxygen is a gas-gas reaction, which is a faster reaction than the combustion of coal which occurs via solid-gas reactions.

Long and others (2006, 2008) combusted PE or mixed waste plastics (both with particle sizes 0–3, 3–5 and 5–10 mm) in an electric furnace under a flow of hot air (1 L/min) and measured the CO and CO₂ contents of the generated gas. They found that the combustion rate of the smaller particles for both materials was faster than the larger particles at 1200°C; but at 1250°C, particle size had little influence on the combustion process. As expected, combustion efficiency (termed combustion ratio and defined as the ratio of carbon content to the original carbon content) of particles with the

same size was better at the higher temperature. Smaller particles had a higher combustion efficiency during the initial 200–600 s, but after this period the combustion efficiency was reversed in that the larger particles had a higher combustion efficiency. The experimental conditions could not supply enough oxygen to combust the material.

The combustion efficiency of pulverised coal (carbon content 82.5%) and its mixtures with 20, 40 and 60 wt% of waste plastics were additionally investigated by Long and others (2006). The pulverised coal had a lower combustion efficiency (combustion ratio) compared to the waste plastic. The combustion efficiency decreased with increasing plastic content for each of the different particle sizes (0–3, 3–5 and 5–10 mm), under the same experimental conditions (1250°C). Overall, the mixture containing the lowest amount of plastics (20 wt%) with the largest particle size (5–10 mm) displayed the highest combustion efficiency (88%). Combustion of the mixtures containing larger proportions of coal took longer to complete.

Li and others (2007) also observed in their simulated BF experiments that the coal-mixed waste plastics blend with the lowest plastic content (15 wt%) and largest particle size (5–10 mm) had the highest combustion efficiency. The combustion efficiency of the blend containing 25 wt% plastic decreased with increasing particle size (0–10 mm), whilst the 15 wt% plastic blend improved slightly with increasing particle size. TGA experiments additionally showed that ignition of blends of coal and mixed waste plastics (with a particle size of 0.1–0.2 mm) occurred at a lower temperature than either the coal (8 wt% VM) or plastics (90 wt% VM) alone. Moreover, the ignition temperature of the blends had a parabola trend with increasing plastic content, with the lowest temperature occurring with a plastic content of 20–25 wt%. The reason given is that the plastic in the blends adhere to the surface of the coal particles. The specific surface area of the blends is larger than the granular plastics alone which leads to the earlier ignition of the coal-plastic blends. The waste plastics included both film and granular plastics. The blends had been prepared by heating the coal and waste plastic mixtures in a kiln at 200°C. The plastic film melts and adheres to the surface of the coal and solid plastic particles, whilst the solid plastics are dehydrated and dechlorinated. The mixtures were then quenched, ground and mixed.

Simulated BF experiments using a hot model, where the injectant is blown into a packed coke bed, found, like the above Chinese studies, that the combustion efficiency of PE (1–10 mm in size) decreased with increasing particle size, and that the effect of particle size decreased with increasing temperature (900–1100°C) and oxygen enrichment (Kim and others, 2002). The combustion efficiency of mixtures of pulverised coal (75 μm) and 10 wt% PE were less than that of the constituent coal, with the mixture containing the largest PE particle size (3–5 mm) having the lowest efficiency. However, the combustion efficiency of coal and the mixtures were of a similar order at locations furthest from the tuyere. The experimental setup figure implies the coal and plastics were injected through separate lances. Heo and others (2000a) also report that the combustion efficiency of plastics in a hot model is lower than that of pulverised coal (VM 26 wt%).

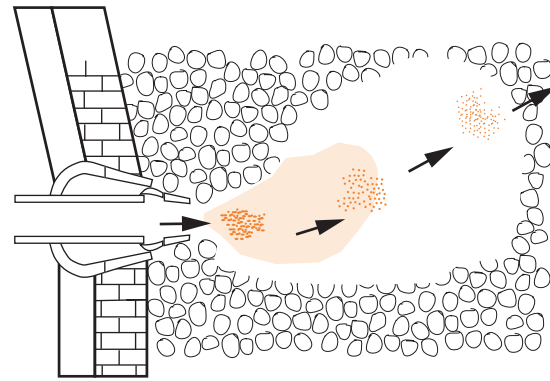
Test injections of waste plastics through separate tuyeres at the Keihin BF1 in Japan indicated that the combustion behaviour of fine waste plastics (0.2–1 mm) was similar to pulverised coal (74 µm), being instantly combusted and gasified at the injection point. On the other hand, the coarser waste plastics (up to 10 mm) were found to burn with greater difficulty compared to the coal (Asanuma and others, 2000). This agrees with the hot model and other experiments discussed above indicating that finer plastics burn closer to the tuyere compared to coarser particles.

However, hot model experiments (at 1200°C) found that the combustion and gasification efficiency of waste plastics improved with increasing particle size (Asanuma and others, 2000, 2009; Sato and others, 2006), unlike the studies discussed above. This is also the opposite to pulverised coal where combustion efficiency generally decreases with increasing particle size. As well as particle size, the combustion behaviour of waste plastic is influenced by its strength. The harder crushed particles had a higher combustion and gasification efficiency than agglomerated plastics of the same particle size, despite the higher combustibility of the agglomerated particles. Crushed particles with a size of 3.5 mm reached almost 100% efficiency whilst the 3.1 mm agglomerated particles only achieved around 80%. Both groups of plastics had a higher combustion and gasification efficiency than pulverised coal, with the exception of the smaller (<2 mm) agglomerated plastic particles (Asanuma and others, 2000; Sato and others, 2006).

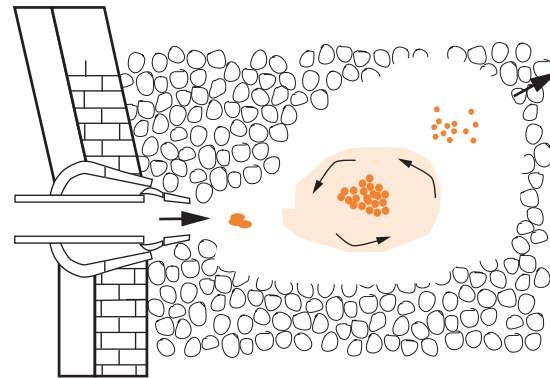
The explanation given for the different combustion behaviour of the waste plastic particles is that the coarse agglomerated particles, produced from film-like plastics, are easily fragmented by thermal shock. The generated fine particles (along with the pulverised coal) are then swept through the raceway by the high velocity hot gas blast into the coke bed. The coarse harder plastic particles (crushed plastics) are too big to pass through the raceway boundary, and therefore circulate within the raceway until their diameter is small enough to allow the unburnt particles to pass into the coke bed (see Figure 14). A three-dimensional mathematical model simulating the gasification and combustion behaviour of waste plastics and coal has been developed. It includes the concept of the circulation of the larger plastic particles within the raceway in a flow submodel (Goto and others, 2008).

Hot model experiments indicated that the combustion and gasification efficiency of agglomerated plastics could be improved by injecting the plastic with pulverised coal through a single lance (see Figure 15). The coal and waste plastics are mixed in the piping just before their injection. This arrangement resulted in about a 10% higher combustion and gasification efficiency than separate injection of the materials. The efficiency values obtained through the single lance arrangement were nearly the same as those obtained for the injection of crushed plastic particles (Murai and others, 2004; Sato and others, 2006). The pulverised coal adheres to the surface of the larger plastic particles (3 mm) after mixing in the piping. The generated heat from combustion of the coal is therefore supplied directly to the plastics, accelerating their combustion. Furthermore, the residence time of the coal in the

fine plastics, pulverised coal



coarse plastics (soft particle)



coarse plastics (hard particle)

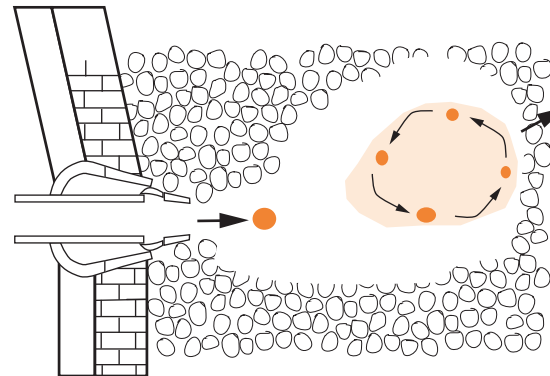


Figure 14 Combustion and gasification behaviour of waste plastics in the raceway (Asanuma and others, 2000)

high temperature area is prolonged, improving its combustibility. However, Sahajwalla and others (2004) found no indication of the adhesion of coal char on partially fused/combusted PE grains when mixtures of coal with 10 wt% linear LDPE were injected in a pilot-scale rig, without a coke bed (residence time was 20 ms). Partial fusion was seen for some of the larger LDPE grains sampled outside the raceway, that is, at long transit times.

Hot model tests showed that the injection of methane through one lance and pulverised coal and agglomerated plastics through another lance increases the combustion and

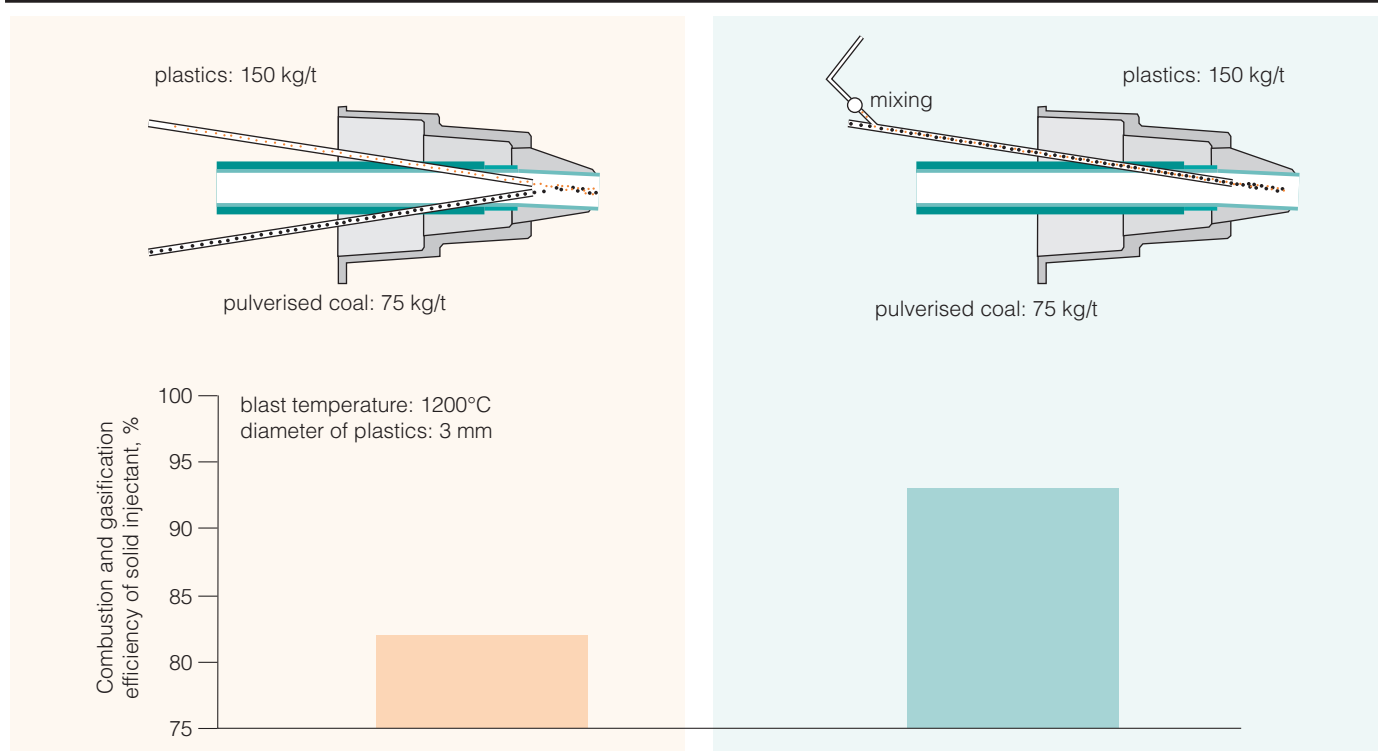


Figure 15 Effect of simultaneous injection on combustion and gasification efficiency (Asanuma and others, 2009)

gasification efficiency of the solid injectants. This method is now used by JFE Steel in their BF_s (Asanuma and others, 2009). Adding calcium carbonate improves the strength of agglomerated plastics, allowing the particles to circulate for a longer time within the raceway. It additionally lowers the melting point of the formed slag, thereby alleviating the pressure drop in the furnace caused by a deterioration in permeability. This technology has been adopted in BF₃ at JFE Steel's West Japan Works (Asanuma and others, 2009; Sato and others, 2006).

Babich and others (2003) report on German work that investigated the combustion behaviour of waste plastics with the same composition (76% carbon, 10% hydrogen, 8% oxygen, 5% ash) and particle size (3–6 mm) but prepared in different ways. Three plastic types were investigated: agglomerate (fraction after crushing and removal of unwanted substances), granulate (after smelting at 100°C) and re-granulate (after additional pressing; it had the highest density). The agglomerated (crushed) plastic had the highest combustion efficiency due to its larger surface area and lowest density, followed by the granulate and then the re-granulate. The combustion efficiency of all three plastic types was low since the large particles could not completely burn out in the available residence time (20 ms).

Morgan and others (1999) injected up to 30% ASR, agglomerated or granular plastic wastes (mm in size) with coal (23 or 25% VM, db, 75 μm particle size) through separate lances or the same lance in a semi-industrial test rig. In both cases, increasing the ratio of waste plastics decreased the heat release rate in the raceway, due to the slow combustion rate of the waste plastic particles. Calculations showed that both the size and shape of the waste material caused the delayed conversion in the raceway. Decreasing the

waste plastic particle size to below 1 mm would enhance the combustion efficiency.

The rank and composition of the coal used in some of the above experimental studies is not always given, so the effect of coal type is not clear. Sahajwalla and coworkers compared the effects of blending PE (linear LDPE or HDPE) with Australian HV (VM 34 wt%, db) and LV (VM 13 wt%, db) coals (Gupta and others, 2006; Sahajwalla and others, 2004). The DTF experiments were carried out at 1200°C under a gas flow rate of 1.22 L/min and fuel lean conditions ($O/C > 2$), with a particle residence time of about 1–2 s (Gupta and others, 2006). The combustion efficiency (burnout) of the 10 to 30 wt% PE blends containing the HV coals were higher than those with the LV coals. Moreover, the combustion efficiency of the coals increased (by about 5%) after blending with plastic, even though the plastic was not completely combusted. It is suggested that the presence of plastic may have helped modify the coal char structure due to heat released by the combustion of the plastic volatiles and hence increased coal burnout. X-ray diffraction studies had indicated that the char structure from the coal-plastic blends were different from those of the constituent coal and plastics. These structural differences could have implications for the kinetics of combustion/gasification phenomena during plastic injection in BF_s.

Babich and others (2002) report on German work that also found that injection of up to 20 wt% waste plastics (PE) with coal gave a higher combustion efficiency than that of the constituent coals. However, the combustion efficiency of the 30 wt% plastics mixture was lower than the coal. Other German work showed that the combustion efficiency of LV coal increased by 10–20% after blending with 10–30 wt% waste plastics (Babich and others, 2003; Gudenau and others,

2003). The waste plastics were ground to below 200 μm (Gudenau and others, 2003).

Gupta and others (2006) found that the improvement of the combustion efficiency of blends was not significantly influenced by an increase in the PE particle size from 100 to 600 μm . The difference in the particle size is not large, especially when compared to studies which used plastic particle sizes up to 10 mm. The particle size of the coal was <75 μm . Up to 30 wt% of linear LDPE or HDPE could be blended with coals without adversely affecting the combustion efficiency of the constituent coals.

Further combustion studies of the LV and HV Australian coals blended with 10 wt% of the linear LDPE (<600 μm) were carried out in a pilot scale test rig with a 1200°C hot blast and a residence time that better simulates the time pulverised coal spends in an industrial BF (about 20 ms). No coke bed is used in the experimental setup. In general, the results did not suggest any enhancement of the combustion performance of coal by the PE, unlike the results from the DTF studies (at a longer residence time). The combustion efficiency (burnout) of the mixtures were similar to, or marginally lower, under fuel lean conditions than the constituent coal in the case of the HV coal blend. For the mixtures with the LV coal, the burnout was lower over the full range of the test conditions. A slight improvement in the combustion efficiency of the HV coal mixture was observed with a finer LDPE particle size, compared to the coarser (<600 μm) plastic blend, particularly under fuel lean conditions (Sahajwalla and others, 2004).

The composition of ASR can vary widely due to differences in the waste treatment processes and the make of vehicle. Hence its combustion and gasification efficiency will vary. TGA of ASR (fluff) indicated that it would have a higher combustion reactivity than coal due to its higher VM content,

low ignition temperature (190°C), and lower combustion start and maximum weight loss temperatures (*see* Table 7). However, the high ash content of the ASR could lead to problems since erosion of the raceway wall occurred with the coal and 10% ASR mixture in pilot-scale experiments (Mirabile and others, 2002).

When 10 to 30 wt% of ASR (shredder light fraction, 30 wt% VM, 66.6 wt% ash) was mixed with bituminous coal (30 wt% VM, 7.7 wt% ash) or lignite (38.7 wt% VM, 15.3 wt% ash), the combustion efficiency (degree of burnout) marginally decreased with increasing proportions of the shredder fraction (Vamvuka and others, 1996). The effect was more obvious in the lignite blend. The particle size of the blends were 63–90 μm . Higher combustion efficiencies were achieved with a larger particle size (125–150 μm for the lignite blend). The shredder fraction had a lower combustion efficiency than both coals mainly due to its high ash content. The samples were blown with hot air into an induction furnace at 1500°C and had a residence time of around 20 ms.

German studies discussed in Babich and others (2003) found that the combustion efficiency of ASR (shredder light fraction) was lower than HV and LV coal. However, the combustion efficiency of LV coal with 20% ASR (30% ash, particle size 0.2 mm) was close to that of the single coal at O/C ratios >2 (Babich and others, 2003; Gudenau and others, 2003).

The combustion and gasification behaviour of the float fraction (organics, crushed to 2–10 mm) obtained from the Thermo-bath treatment process of ASR (*see* Section 4.2) was investigated using hot model tests with a 1200°C hot blast (Takaoka and others, 2003). Table 8 gives the composition of the floats, pulverised coal and plastics used in the test. The CO₂ peak (a measure of combustion efficiency) in the

Table 7 TGA of coal and ASR (Mirabile and others, 2002)

	VM, %	Ash, %	Start combustion temperature, °C	Maximum weight loss temperature, °C*
Coal: reference	24.9	10.1	310	530
Coal A, low ash	17.8	4.8	400	550
Coal B, high volatile	28.5	9.3	310	540
Coal C, low volatile	11.7	10.7	370	550
ASR (fluff)	54.2	36.2	300	350

* this value is determined by evaluating the temperature where zero is the derivative $\delta m/\delta t$ (of the curve dm versus T)

Table 8 Composition of the floats, pulverised coal and plastics (Takaoka and others, 2003)

	Proximate analysis, dry, wt%			Ultimate analysis, dry, wt%				
	VM	Fixed carbon	Ash	C	H	N	S	O
Floats	70.0	22.3	7.7	80.2	5.82	1.33	0.24	3.39
Pulverised coal	25.8	63.8	10.4	77.0	3.94	1.8	0.48	6.38
Plastics	93.8	2.2	4.0	77.3	12.2	0.15	trace	6.35

resultant gas composition was nearest to the tuyere for the pulverised coal, followed by the floats, plastics and then all coke operation. The combustion and gasification efficiency of the floats was higher than pulverised coal (about 60%) and about the same as for the plastics (around 80%). This was attributed to the longer residence time of the floats in the raceway. Like plastics, the floats are dense and are not fragmented by the rapid heating in the raceway. Hence they circulate for longer periods in the raceway whilst the fine coal particles are swept through the raceway by the high velocity gas. A 1500 kg/h floats injection test in a commercial BF found no degradation in the furnace top gas, dust, hot metal and slag. The test only lasted for 2 h.

5.3.3 Summary

In general, the combustion efficiency of coal decreases with increasing particle size. However, it is not so clear cut with plastics. Some workers have reported the same effect with PE, whilst Asanuma and coworkers have shown the reverse – that the combustion efficiency of waste plastics increases with increasing particle size. This was attributed to the properties of the plastics, particularly their strength. The larger plastic particles that do not fragment (the higher density plastics), circulate within the raceway until they become small enough to escape through the raceway boundary. This was despite the fact that the agglomerated plastics have a higher combustibility than the higher density crushed plastics. The particle size and density of waste plastics is controlled by the treatment facility.

Operating conditions also play a role. The particle size effect for coal was shown to be partly dependent on oxygen stoichiometry, as well as coal rank (Vamvuka and others, 1996). Oxygen stoichiometry is likely to influence the combustion efficiency of plastics. The effect of particle size decreases with oxygen enrichment and temperature (Kim and others, 2002; Long and others, 2006, 2008).

Injecting coal with plastics indicated that the highest combustion efficiency was achieved with the lowest amount of PE (<20 wt%) but containing the largest particle size (5–10 mm). The combustion efficiency of coal and plastics co-injection is probably influenced by both the coal and plastics properties, as well as the operating conditions. Synergetic effects between coal and plastics have been reported. For instance, the combustion and gasification efficiency of agglomerated plastics improved when injected with coal due to the adhesion of coal to the surface to the plastic particles (Asanuma and others, 2009; Sato and others, 2006). Injecting waste plastics enhances the combustion efficiency of LV coal (Babich and others, 2003; Gupta and others, 2006). This was attributed by the latter authors to the modification of the coal char structure due to heat released by the combustion of the plastics volatiles. However, pilot-scale tests at a shorter residence time indicated little combustion enhancement (Gupta and others, 2006). The blends, though, only contained a small amount of PE (10 wt%). Pyrolysis studies of LDPE, HDPE, PP (all with particle size <500 µm), LV coal (20 wt% VM, db, particle size <150 µm) and their mixtures in a TGA under an inert atmosphere indicated that

the synergetic effect occurs mainly in the high temperature region (the samples were heated up to 750°C) (Zhou and others, 2009).

The variety of test rigs and test procedures used may help explain some of the contradictory results published in the literature. For instance, the residence time varies from seconds in a TGA to ms in pilot-scale rigs. Results are also influenced by the design of the test rig. Mathieson and others (2005) found that the test rig configuration had 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 number of studies carried out on co-injection of coal and waste plastics is small, and the properties of the coal used are not always given. More work is needed to validate the effects of coal properties on plastics behaviour, and the influence of operating conditions.

5.4 Operational factors

The effective use of coal and waste plastics requires operational changes to compensate for alterations in the raceway parameters and their effect elsewhere in the BF (such as the thermal state, slag regime and gas dynamics). Injecting waste plastics up to 10 kg/thm is not expected to disturb BF operation (Ziębik and Stanek, 2001). Measures to intensify the combustion of coal and waste plastics in the tuyere/raceway region, and hence increase injectant rates, include:

- increasing the amount of oxygen in the tuyeres;
- adjusting blast temperature and moisture.

Other measures taken to improve coal combustion, such as preheating the coal and the use of additives, are covered in Carpenter (2006). As noted in the previous section, the choice of particle size, and hence the grinding parameters, can also influence the combustion efficiency.

5.4.1 Oxygen concentration

Oxygen can be added to the tuyere by:

- enrichment of the hot air blast;
- injection through the coal and waste plastic lances; and
- separate oxygen lances.

The addition of oxygen means more oxygen is available for participation in the combustion of coal and waste plastics in the raceway. Consequently their combustion efficiency increases (Borrego and others, 2008; Cao and others, 2005; Carpenter, 2006; Gao and others, 2008; Gupta and others, 2006; Heo and others, 2000a; Kim and others, 2002; Zevenhoven and others, 1997). Nevertheless, 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 (34.4% VM) and 3.31% for a LV coal (13.8% VM) when oxygen enrichment

of the hot air blast is raised from 0 to 6 vol%. With higher oxygen enrichment, combustion efficiency can actually decrease due to insufficient mixing. Increasing oxygen enrichment enhances the diffusion of oxygen, but diminishes the volume of combustion gas that transfers heat to the injectant particles. DTF experiments carried out by Gupta and others (2006) found that the improvement in the combustion efficiency of coal-PE blends was not significant when oxygen enrichment exceeded 3%. Thus the non-linear effect of blast oxygen content on the degree of injectant combustion has to be taken into account.

Oxygen enrichment of the hot air blast produces both a reduction in bosh gas flow and a rise in flame temperature (Carpenter, 2006). The former effect can help counteract the increase in burden resistance (lower permeability) and the pressure drop associated with high injectant rates. The latter effect can help compensate for the cooling effect of the decomposition of the coal and waste plastic volatiles. The CO and H₂ contents also increase with oxygen enrichment, resulting in improved reduction of the iron ores in the central shaft. The calorific value of the BF top gas usually improves with oxygen enrichment.

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 the injectant increases. If the flame temperature becomes too high, then burden descent can become erratic. Too low a flame temperature hampers coal and waste plastics combustion and melting of the ore burden (Geerdes and others, 2004). 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.

The position and design of the injection lance influence combustion efficiency and ash deposition in the tuyere. The injection of oxygen through lances is discussed in Carpenter (2006) for coal. However, oxy-coal lance injection (co-annular injection) can produce an insulating effect around the coal particles, resulting in less coal combustion inside the tuyere. This effect carries over into the raceway, and less combustion is the end result. Lowering the oxygen lance injection rate in these cases would improve combustion efficiency (Walker and others, 2008). There is little information on the use of oxy-waste plastic lances or separate oxygen lances in WPI.

5.4.2 Blast temperature and moisture

The key measure for combustion at high injectant rates 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 injectant combustion (Zhang and Bi, 2003). Generally, a higher hot blast temperature is a cheaper measure than oxygen enrichment since it allows a lower oxygen consumption. Increased blast temperatures also

reduce coke consumption, typically 10 kg/thm for every increase of 40°C with PCI (Poveromo, 2004), and lead to a small rise in the raceway depth (Babich and others, 2002).

A higher blast temperature is generally required as the coal VM increases (Carpenter, 2006). This has been attributed to the lower char reactivities of the lower volatile coals (*see* Section 5.2.1). Waste plastics can have a stronger cooling effect on flame temperature than coal (*see* Section 5.2.2). Although increasing the blast temperature raised the RAFT with waste PE injection, it was found that regardless of the blast temperature (900, 1000, and 1100°C) and oxygen enrichment (0.7 and 1.2%), the maximum RAFT that could be achieved was around 1950°C. This suggests that blast temperature and oxygen enrichment only affect the combustion kinetics (rates), and not the thermodynamics; as long as the plastic particles start burning, the maximum temperature related to the enthalpy of combustion remains constant (Kim and others, 2002).

Lowering blast moisture can help to compensate for the cooling effects of PCI and WPI. If the RAFT becomes excessive, then blast moisture can be increased. Raising hot blast moisture means more H₂ in the bosh gas for iron ore reduction. The optimum RAFT in furnaces operating with higher H₂ contents can be lower than those operating with lower H₂ (*see* Section 3.2.2).

In addition, the blast velocity can be adjusted to not only improve injectant 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 Unburnt char

As the injection rate increases, the combustibility of coal and waste plastics tends to decrease resulting in unburnt material (char, fines and fly ash) exiting the raceway. Some of this material, along with coke debris, accumulates 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, decreasing permeability and hence furnace productivity. Changes in the lower furnace zone permeability can additionally affect the hot metal quality and slag viscosity. The unburnt material tends to accumulate at positions where large changes in gas flow occur. Eventually it is entrained into the gas flow, passing through the cohesive zone coke slits, and up the stack, where it can influence burden permeability, and is finally emitted with the offgas. Higher coal and waste plastics injection rates also increase the volume of combustion gases, and hence the gas flow, and change the heat load in the lower part of the furnace. In addition, more slag is produced.

The deposition of unburnt fine material is a complex phenomenon consisting of several generation mechanisms, reactions, multiphase flow, accumulation and re-entrainment. Various gas flow models have been developed to understand and predict the behaviour of fine material within BFs. 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.

Operating experience has shown that most of the unburnt material (char) is consumed within the furnace. The three mechanisms for this are:

- gasification with CO_2 and H_2O ;
- 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 lowering the amount of unburnt solids in the offgas. This chapter discusses each of the above char consumption processes.

6.1 Char gasification

The reaction of chars with CO_2 and H_2O begins in the raceway, but since the residence time for fine particles is too short for appreciable reaction, gasification mainly occurs in the furnace shaft. The reactions of char carbon with CO_2 (the solution loss or Boudouard reaction) and H_2O are slower than char combustion. The chars derived from coal, waste plastics/ASR and coke compete with each other for CO_2 and H_2O . Chars from coal and waste plastics are more reactive than those from coke and consequently are preferentially gasified (Akiyama and Kajiwara, 2000; Asanuma and others, 2000; Gudenau and others, 2003). Thus coke degradation by the solution loss reaction decreases with increasing PCI and WPI rates.

In general, high VM coal chars have a higher CO_2 reactivity

than low VM coal chars (Carpenter, 2006; Chen and others, 2007). Thus the reactivity of low VM coals can be improved by blending with high VM coals. The CO_2 reactivity of coal blends (in this case, subbituminous and bituminous coals in a TGA at 1050°C) are non-additive (Osório and others, 2006).

Asanuma and others (2000) report that the CO_2 gasification rate of char from agglomerated waste plastics (particle diameter $400\text{--}500\ \mu\text{m}$) is about 10 times higher compared to the pulverised coal ($50\ \mu\text{m}$), despite their larger size. The rates were determined using a thermobalance. The CO_2 gasification rate of PVC char is also slightly higher than coal char (Zevenhoven and others, 1997). However, Murai and others (2004) estimated that the reaction rate of unburnt char from waste plastics ($300\text{--}400\ \mu\text{m}$) is about half that of coal char ($50\ \mu\text{m}$). Although waste plastics char has a longer residence time in the packed coke bed due to its larger size, it has a small gasification rate because of its fairly small specific surface area. Consequently, it could accumulate in the lower part of the furnace, decreasing permeability, unless combustion efficiency in the raceway is high. Decreased permeability occurred in test injections of 6 mm sized PBT and PE (injection rates $2.5\text{--}13.8\ \text{kg/thm}$) in a South Korean BF (Heo and Baek, 2002; Heo and others, 2000b).

The reactivity of carbon in the unburnt char to CO_2 and H_2O is dependent not only on its surface area (particle size) but also on its structure and composition, as well as operating conditions (Carpenter, 2006). Experiments in a WMR found that CO_2 gasification reactivity of bituminous coal chars increases with temperature up to 1500°C , especially between 1300 and 1500°C (Gao and others, 2008). Complete char gasification was achieved with a contact time of about 10 s at 1500°C . Since the residence time for particles at such high temperatures is too short in a BF, char gasification will mainly occur at decreasing temperatures in the furnace shaft.

The properties of char change as it moves up the furnace, and hence its reactivity to CO_2 and H_2O . The reacting environment is not uniform; for instance, the concentrations of CO , CO_2 , H_2 and H_2O vary at different locations within the furnace. Measurements at the Keihin BF1 in Japan found higher H_2 and CO concentrations at the periphery compared to the centre of the furnace for waste plastics with a particle size of $0.2\text{--}1\ \text{mm}$ (see Figure 16); but the reverse occurred when larger particles ($\sim 10\ \text{mm}$) were injected (Asanuma and others, 2000). Injecting coal and waste plastics increases the bosh gas H_2 concentration. Since the chemical reaction rate of H_2 reduction is higher than that of CO , the extent of solution loss reaction will diminish as bosh gas H_2 rises.

CO_2 and H_2O are present in the upper part of the furnace due to the reduction of iron ore. Under the conditions here, char gasification by CO_2 is likely to be controlled by the rate of the chemical reactions. In the lower part of the furnace, char gasification is partly diffusion controlled. Therefore the overall reaction rate of char gasification is likely to be influenced by the chemical reactivity of char to CO_2 in this

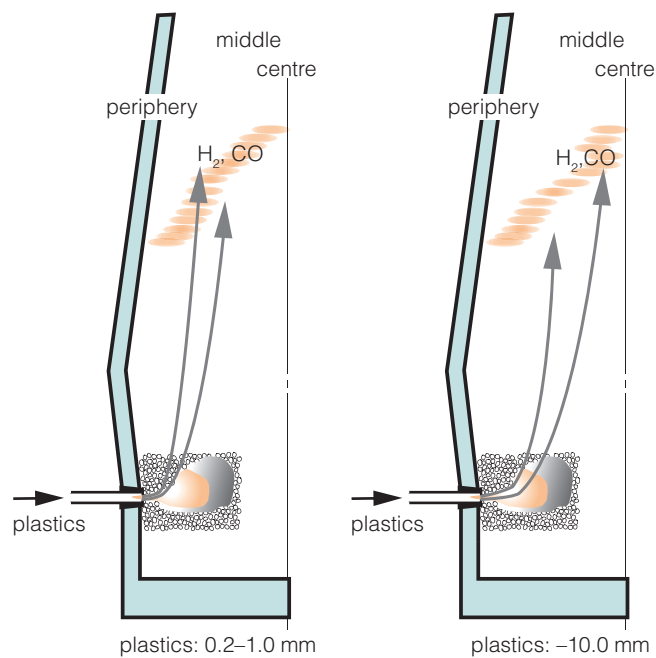


Figure 16 Gas flow generated from waste plastics within the furnace (Asanuma and others, 2000)

region (Lu and others, 2002). Char reactivity towards CO_2 is influenced by its chemical structure, with less ordered structures being more reactive. The char structure from agglomerated waste plastics has an isotropic texture with high CO_2 reactivity (Asanuma and others, 2000).

The presence of certain minerals in the char ash, such as iron and alkalis, can catalyse the CO_2 gasification reaction, whereas other minerals, such as silica and alumina, can slow down the reaction. These catalytic effects become more pronounced for low rank coals. Depending on its composition, ash may also retard the carbon conversion due to blockage of char particles as a consequence of increased proportion slag formation in the char particle (Bennett, 2007). In the lower part of the furnace, condensed alkalis from the recirculating gases (derived from coal, coke and iron ore) could have a catalytic effect. The loss of carbon by gasification will increase the char ash content. In general, waste plastics have a lower ash (mineral) content than coal (see Table 5 on page 18) and therefore are more likely to be consumed within the furnace. Only small amounts of untreated ASR can be injected into BFs, partly due to its high ash content. Treated ASR can have a lower ash content than coals (see Table 8 on page 36). Co-injecting waste plastics/ASR and coal should lower the amount of char originating from the coal.

6.2 Interactions with liquid metal

Carburisation of the hot metal begins in the solid phase within the cohesive zone of the furnace, and continues during descent of the metal droplets through the active coke, deadman and hearth zones. Unburnt char and fine material exiting the raceway can contact the dripping molten metal in the bosh and hearth zones. Carbon and other elements, such as iron, silicon and sulphur, dissolve from the char into the

liquid iron influencing the composition of the hot metal product. 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. If the hot metal is close to saturation when it reaches the deadman and hearth, the unburnt material cannot be consumed, thus diminishing permeability in these regions. The carbon can come from unburnt coal and waste plastic materials, as well as coke. Since the dissolution rate of carbon from coal char is a slower process than that from coke (Carpenter, 2006; McCarthy and others, 2002), coke carbon may be preferentially consumed. There is little published work on the dissolution rate of carbon from waste plastic char; the mechanism of its consumption is likely to be similar to coal and coke.

Carbon dissolution from unburnt char into liquid metal is influenced by the operating conditions and factors such as the:

- char particle size. Unburnt chars that maintain their pulverised form react very little with the liquid iron and slag as they 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 BF6 in 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, though, have shown that the dissolution rate of carbon from coal char, albeit at larger particle sizes, is a slower process than that from coke;
- char structure. Generally, the rate of dissolution improves as the carbon structure becomes more ordered;
- char mineral matter. In general, SiO_2 , MgO and Al_2O_3 slow the carbon dissolution kinetics, whilst CaF_2 and iron oxides enhance the rate. The effect of CaO is less clear (Carpenter, 2006; McCarthy and others, 2002). The reaction of calcium with sulphur in the metal produces a calcium sulphide layer that may inhibit carbon transfer. The ash fusion temperature (AFT) is also 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;
- liquid metal composition, which changes over time. The carbon dissolution rate typically decreases as the carbon content of the molten metal increases. Higher sulphur contents also retard carbon dissolution. Combustion of coal, waste plastics and coke releases sulphur oxides which can react with the descending metal (and slag). This is less of a problem with waste plastics since they typically have a lower sulphur content than coal and coke.

More details about the processes can be found in Carpenter (2006).

6.3 Interactions with slag

Unburnt char, ash, fines and coke can interact with the dripping slag. 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 (Carpenter, 2006).

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 coal 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 unburnt 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. The wetting characteristics have a significant effect on the dominant reduction mechanism taking place. The wetting characteristics of slags vary with slag composition, temperature, time, and carbonaceous material (Mehta and Sahajwalla, 2000, 2001). 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. Reduction rates generally increase with increasing slag FeO (2–10 wt%) contents (Sarma and others, 1996) and with increasing reaction temperature (1300–1600°C). In general, coal chars are poorly wetted by slags containing more than 10 wt% iron oxide at 1400°C and 1500°C (Mehta and Sahajwalla, 2000, 2003; Teasdale and Hayes, 2005). A faster reaction rate for coke suggests that coke fines would be preferentially consumed before coal char;
- reduction of silica in slag by char carbon. This 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 (Mehta and Sahajwalla, 2003). Wetting behaviour improved with an increase in slag silica content, and with an increase in temperature (1500–1700°C). Higher amounts of silica and iron oxides in the char ash facilitates the slag/carbon interactions, leading to improved consumption of these oxides through reduction reactions;

- 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).

6.4 Slag viscosity

The presence of unburnt char 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. A high viscosity slag around the tuyeres would lead to serious gas flow problems.

Slag viscosity is a complex function of slag composition, temperature and oxygen partial pressure. As well as unburnt char and coke, unburnt ash from the coal and some waste plastics and ASRs can interact with the slag. All of these carbonaceous materials contribute oxides to the slag. In general, higher amounts of SiO₂ or Al₂O₃ (acidic components) increase slag viscosity, whereas a higher basicity (higher CaO or MgO) lowers slag viscosity because of depolymerisation of the silicate network (Carpenter, 2006). 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/SiO₂ 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. The addition of fluxes can help solve slag formation problems.

7 Hot metal quality

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 (*see* Table 9) are preferred in order to reduce the refining costs in the steel shop. The principal impurities of concern originating from coal and waste plastics/ASR are silicon, sulphur and trace metals.

Table 9 Typical hot metal specification (Geerdes and others, 2004)

Component	
Silicon, %	0.3–0.7
Manganese, %	0.2–0.4
Phosphorus, %	0.05–0.13
Sulphur, %	<0.03

7.1 Silicon

As well as lowering refining costs, a low metal silicon content reduces BF energy consumption since the silicon transfer reactions are endothermic. 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 coal, coke and the iron ore, pellets and sinter. It can also come from ASR, such as the shredder light fraction. Other waste plastics typically have a low silicon content. A material balance carried out in the Sollac Fos BF (now ArcelorMittal Fos-sur-Mer) in France with PCI found that the iron-bearing materials (sinter) contributed the highest amounts of silicon (76% relative contribution), followed by coke (12%) and then coal (8%). The rest come from the iron ore and pellets (4%). Most of the silicon ended up in the slag (94%) with 4% in the hot metal and 2% in the dust (Steiler and others, 1998).

Transfer of silicon into the hot metal and slag takes place in the lower part of the BF principally via gaseous silicon monoxide (SiO). The silica is partially reduced by carbon present in the raw materials to either gaseous SiO or solid silicon carbide (SiC). The SiC can be further oxidised to SiO by reaction with CO. Carbon in the hot metal then reduces the SiO to silicon. Gaseous SiS can also play a role in silicon transfer. Experiments have shown that the SiO generation rate from coal char is greater than that from coke which, in turn, is greater than that from iron ore slag (Carpenter, 2006).

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. Reactions in the hearth between the hot metal and slag will determine the final amount of silicon in the tapped metal. As the metal droplets trickle through the slag layer, part of the silicon already

picked up by the iron reacts with oxides in the slag resulting in silicon removal from the metal.

The hot metal silicon content can be controlled by a number of factors:

- utilising coal and coke with a low silica content;
- co-injecting waste plastics since they contain little or no silicon, as was demonstrated at Keihin BF1 in Japan (Wakimoto, 2001);
- lowering the RAFT to reduce the production (gasification rate) of gaseous SiO. This, though, can decrease the hot metal temperature;
- controlling the cohesive zone height. A low cohesive zone height can help decrease the temperature at the tuyere level, diminishing the SiO generation rate;
- controlling slag composition in the high temperature zone. Acidic slags generate SiO, whereas slags with a high basicity (low SiO₂ activity) and high FeO absorb SiO, oxidising it to silica. Injecting iron oxides or fluxes into the tuyeres increases tuyere slag basicity and hence lowers silicon hot metal content. However, if the basicity is too high, slag viscosity increases and the SiO absorption rate will decrease. Lower temperatures promote the silicate capacity of the slags. Operating with a low cohesive zone produces slags with a higher FeO content that absorb the SiO. Desilicisation of the hot metal in the packed coke bed and hearth regions can be enhanced by a suitable slag chemistry. FeO and MnO in the slag can oxidise silicon at the metal-slag interface to silica, transferring silicon to the slag. Increasing the availability of oxygen at the metal-slag interface also enhances metal desilicisation.

The interplay of the many mechanisms affecting silicon transfer to the hot metal and the different BF operating conditions may explain why some operators report lower silicon metal contents with PCI, whilst others found higher silicon levels. More details about the mechanisms can be found in Carpenter (2006).

7.2 Sulphur

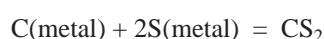
A low hot metal sulphur content is preferred to avoid expensive desulphurisation in the refining plant. Additionally, sulphur in the hot metal retards carbon dissolution from coal char (and coke) and hence char consumption. Most of the hot metal sulphur originates in the coal and coke, although some waste plastics/ASRs, such as waste packaging, can also have a significant sulphur content (*see* Table 5 on page 18).

The principal mechanism for transferring sulphur to the metal is via SO₂ emitted from the coal and coke mineral matter (and, if present, from waste plastics/ASR). Carbon in the hot metal reduces SO₂ to sulphur. Gaseous SiS, formed by the reaction of CaS in the coal and coke minerals with gaseous SiO, also transfers sulphur (and silicon) to the hot metal (Carpenter, 2006).

The hot metal sulphur content can be controlled by:

- utilising low sulphur coals and cokes;
- co-injecting waste plastics that have a low sulphur content. This will also lower the consumption of fluxes and additives added to improve the slag sulphur uptake;
- adjusting furnace conditions to manipulate the partition of sulphur between the gas, metal and slag phases. Of course, control of the sulphur content can only be considered in connection with other requirements of the BF process.

Gas phase desulphurisation of the hot metal (around the raceway) becomes important when sulphur concentration is higher than 0.1% for high carbon metal (Carpenter, 2006). The possible reactions are:



Since the reaction rate of the first reaction, which produces gaseous H_2S , is larger than those of the other two reactions, an increase in the partial pressure of hydrogen will enhance gas desulphurisation. Consequently gas phase desulphurisation plays a larger role with higher injection rates of coal and waste plastics since the amount of hydrogen in the furnace increases.

Sulphur is transferred to the slag as the iron droplets flow down through the coke bed. Oxides in the slag react with sulphur in the metal to form sulphides. The transfer is promoted by a high slag basicity, high temperatures, a high slag reduction degree and a low oxygen potential. Fluxes can be injected to increase slag basicity. Unfortunately, it is difficult to remove sulphur and unwanted alkalis 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. 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.

7.3 Trace metals

Non-ferrous metals present in waste plastics and, in particular, ASR, can adversely affect hot metal quality, which is difficult

to rectify at a later stage. One of the main problems resulting from the test injection (44 kg/thm) of shredder light fraction at EKO Stahl's (now ArcelorMittal Eisenhüttenstadt) BF6 in Eisenhüttenstadt, Germany, was the increase of copper in the hot metal (Korobov and others, 2003). Table 10 gives the chemical composition of ASR taken from an Italian dump. The material was reduced to a 2 mm size before analysis. Copper, nickel, chromium and zinc are among the metals that are not easily vaporised and consequently would principally transfer to the hot metal and slag. The ASR therefore needs to be treated to provide an organic rich fraction (*see* Section 4.2) before significant amounts of the can be injected. Non-ferrous metals also originate in coal, coke, and iron ore, pellets and sinter. Coals with a phosphorus content below 0.08% are usually preferred.

Thermodynamics and metallurgy within the BF concentrate the trace metals into the different output streams. The more volatile elements, such as cadmium and mercury, exit in the offgas and are removed in the gas cleaning system (*see* Section 8.2). The less volatile ones, such as zinc and copper, partition between the liquid metal and slag. Buerger and others (2007) investigated the fate of zinc, lead, cadmium and mercury when waste plastic pellets were injected into voestalpine Stahl's BF A in Linz, Austria (along with heavy oil instead of coal). The waste plastic material is provided by AVE, who process household and commercial waste plastic streams, and TBS (Technische Behandlungssysteme), who treat ASR. An element flow analysis for the BF process was conducted during a three month trial with a waste plastic injection rate of 35 kg/thm. The distribution of the four elements within the input and output flows is shown in Figure 17. The element flow named 'Delta' in the Figure represents the amount of mercury or cadmium in the materials flow where the content was too low to be analysed. For zinc and lead, 'Delta' represents the 'unsteadiness' of the analysis.

The majority of the zinc from all the input sources dissolves into the hot metal because of the overpressure in the BF process, with around 70% leaving in the hot metal and slag. The additional zinc input from the waste plastics was found to be insignificant. Lead has a lower evaporation temperature than zinc, and can accumulate in the furnace, lowering productivity. It is principally emitted in the offgas (absorbed on the dust particles), where it is removed in the gas cleaning system. Its transfer into hot metal is considered to be of minor importance. Both cadmium and mercury were emitted in the offgas and were not found in the hot metal or slag.

Table 10 Chemical composition of ASR (Mirabile and others, 2002)

Carbon, %	49.5	Phosphorus, %	0.7	Iron, %	25.7
Hydrogen, %	5.3	Chromium, %	0.08	Titanium, %	0.9
Oxygen, %	6.9	Copper, %	1.2	Moisture, %	2.2
Nitrogen, %	4.5	Zinc, %	1.9	Ash, %	36.2
Chlorine, %	0.5	Nickel, %	0.07	VM, %	54.18
Sulphur, %	0.2	Lead, %	0.2	CV, MJ/kg	16.72
Fluorine, %	0.05	Silicon, %	2.1	Density, kg/m ³	359

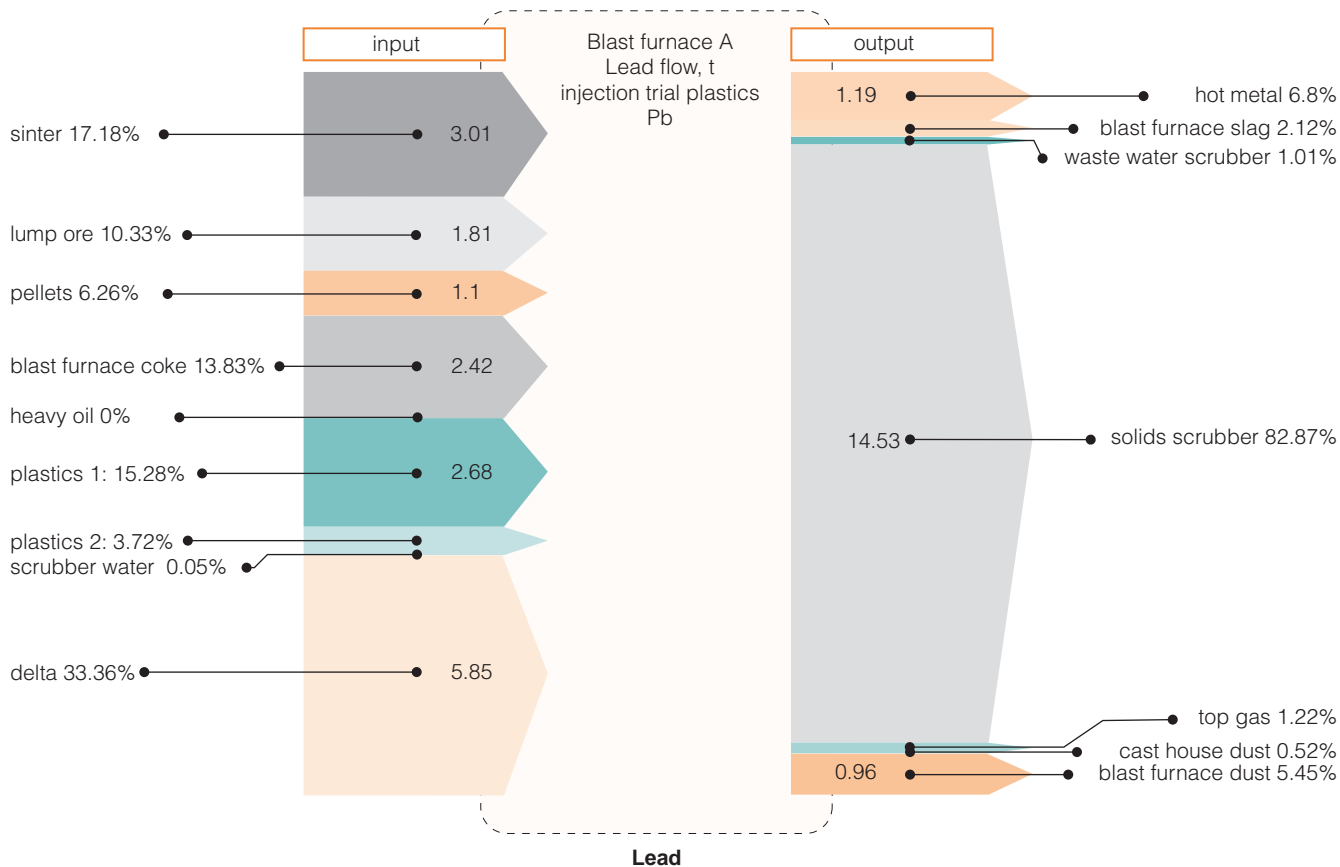
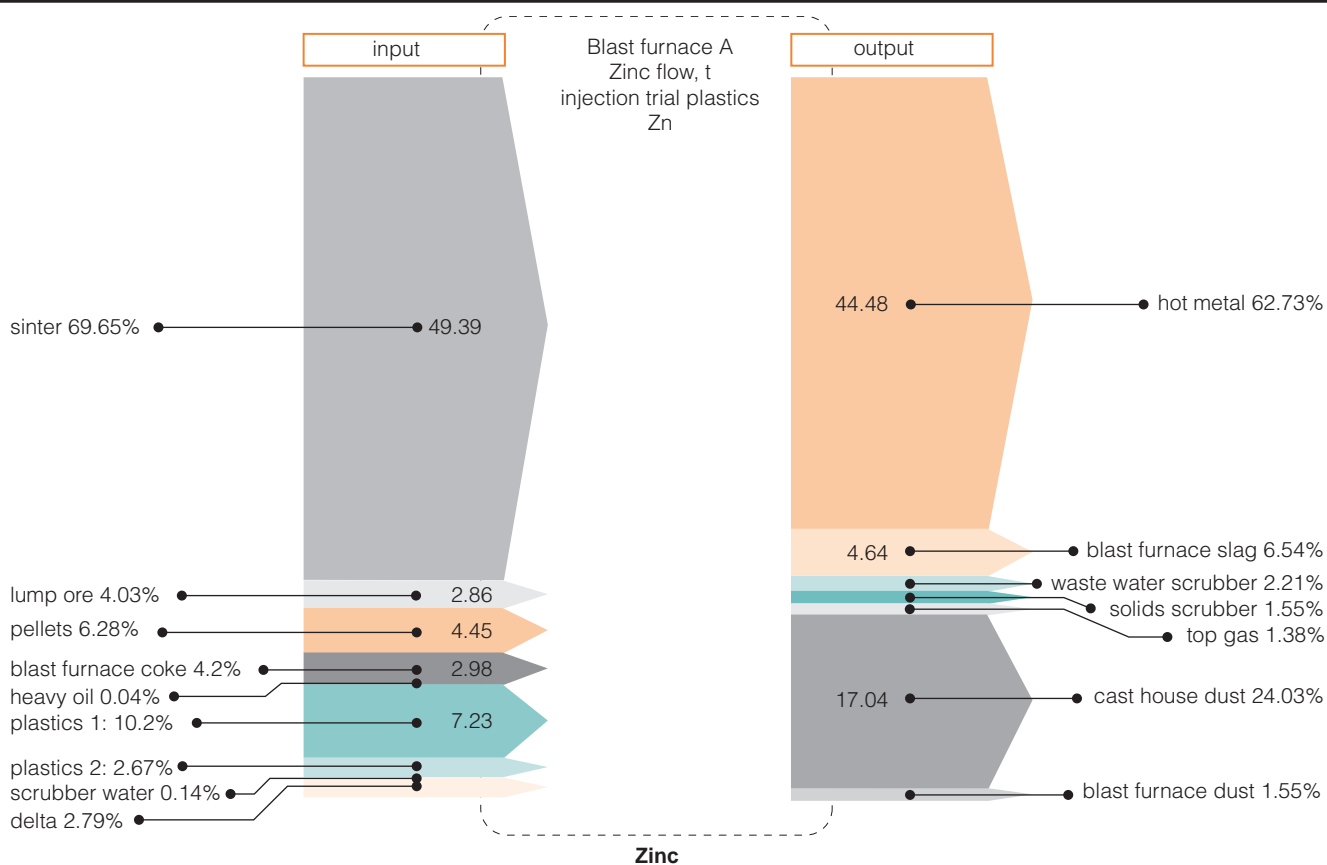
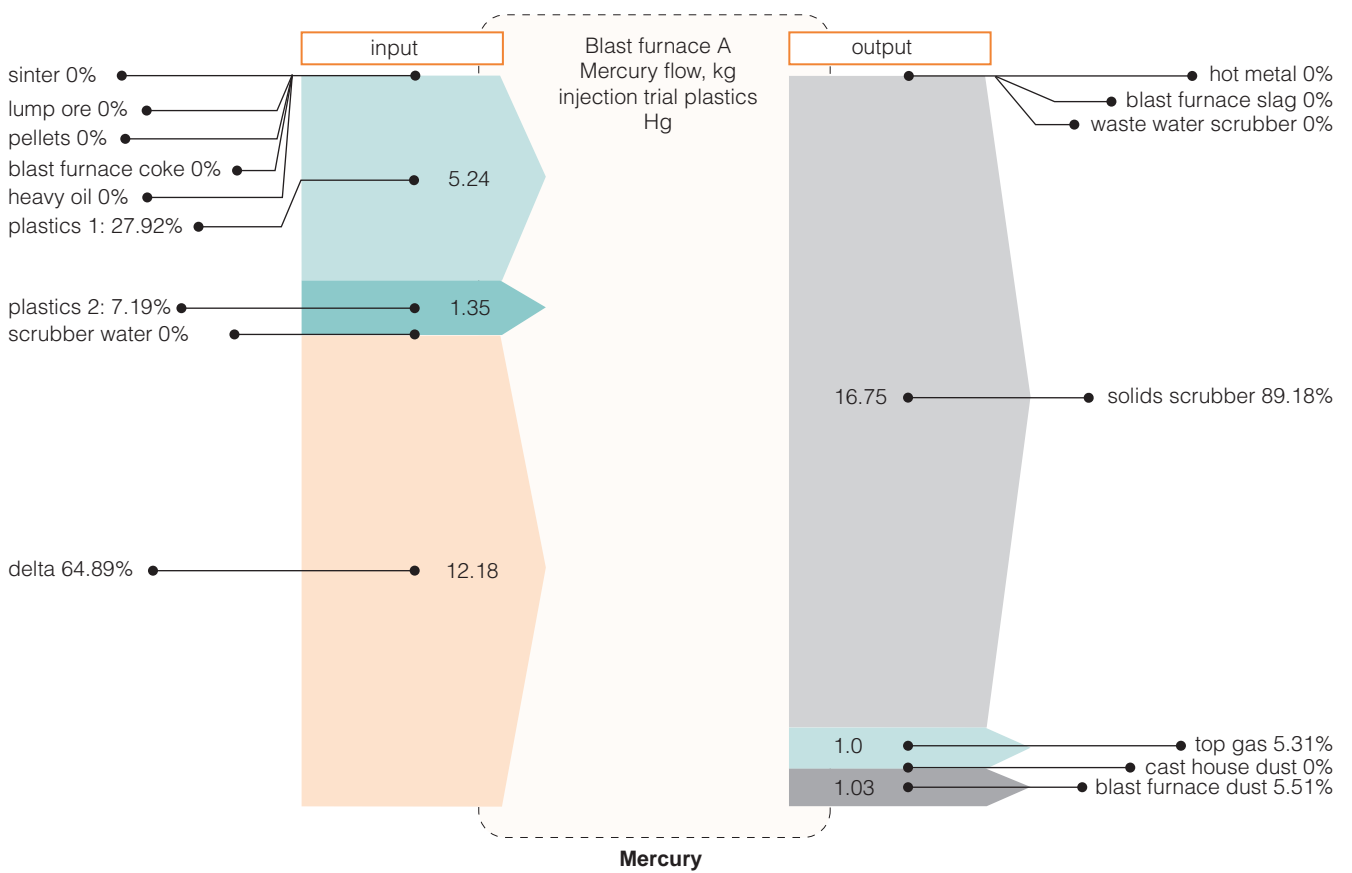
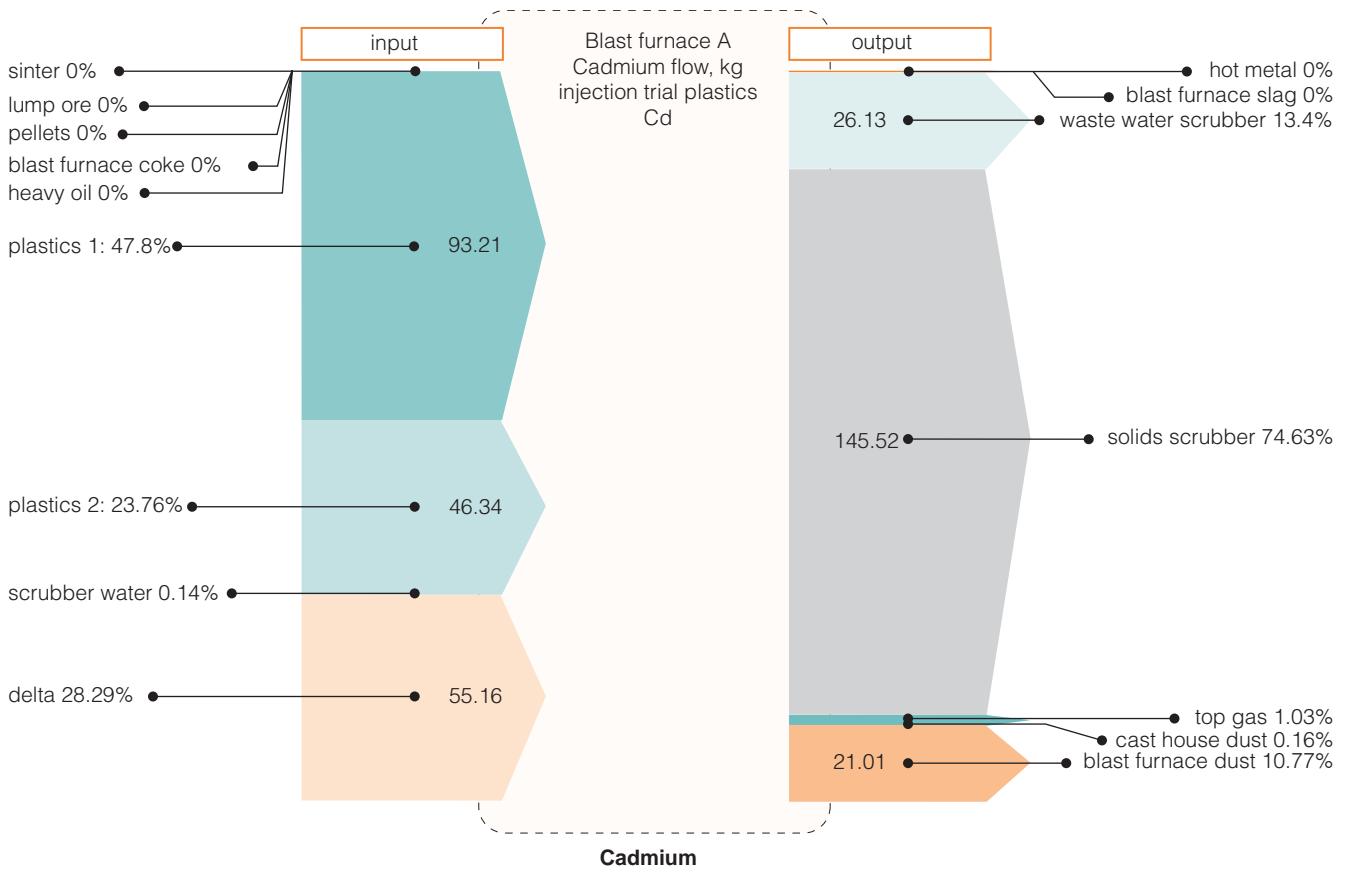


Figure 17 Element flow analysis (Buerkler and others, 2007)



8 Environmental aspects

Globally the iron and steel industry accounts for the highest share of CO₂ emissions from the manufacturing sector, at about 27%. This is due to the energy intensity of steel production, its reliance on coal as the main energy source and the large volume of steel produced (IEA, 2007). Around 60% of steel production is currently produced via the BF route (Carpenter, 2006). BFs are one of the major sources of emissions within a steelworks, and most of the energy consumption is related to the BF process at around 10–13 GJ/t crude steel, including the hot stoves (IEA, 2007). Since CO₂ is associated with climatic change, its abatement is an important consideration. This chapter begins by examining the amount, composition and CV of the offgas (also termed top gas or blast furnace gas), before discussing air emissions. CO₂ emissions and their abatement are then examined in more detail. Finally, liquid and solid wastes are briefly described.

8.1 Offgas

The hot dirty offgas exits the top of the furnace, under pressure, and passes through a gas cleaning system where the particulates (principally unburnt char, soot and coke fines) and water are removed, and the offgas is cooled. The amount of dust to be removed increases with increasing coal and waste plastics injection rates. Modern gas cleaning plants are multiple-step systems where the coarse particles are first removed by gravity separation (dust catchers or cyclones), followed by fine dedusting by wet scrubbers or wet electrostatic precipitators to reach a dust content below 10 mg/m³. voestalpine Stahl's BF A at Linz, Austria, is currently achieving a daily average of 1 mg/m³ (Buerger, 2009b). The modern systems even allow the extracted dust to be sorted into different types for effective re-use.

The offgas contains about 4% H₂, 25% CO, 20% CO₂, with the remainder being principally nitrogen (IEA, 2007). It has a CV of about 3.4 MJ/m³; around 35–40% of the energy content of the coal and coke is extracted from the furnace in the offgas. The cleaned offgas is used for hot blast stoves heating, electricity production, steam generation and/or other uses within the steelworks. Otherwise, surplus offgas can be sold. The CV of the offgas influences its use in downstream processes and saleability.

Many BFs are operated at high pressure to increase furnace productivity. For these plants, a top-pressure recovery turbine can be used to generate electricity from the pressure remaining in the offgas. The power output of top-pressure recovery turbine can cover around 30% of the electricity necessary for all equipment for the BF, including the air blowers (IEA, 2007).

The amount, composition and CV of the offgas is influenced by the properties of the coal and waste plastics, as well as the operating conditions. For instance, HV coals typically have a higher H₂ content and lower CV than LV ones, and

consequently could generate an offgas with a higher H₂ content and lower CV. Injecting HV coals typically increases the amount of dust in the offgas compared to LV coals (Sahajwalla and Gupta, 2005; Ökvist and others, 2006). The amount of fine dust in the offgas was higher when an ultrahigh VM Indonesian coal was injected at the IJmuiden BF6, Netherlands (Toxopeus and others, 2002). The increased carbonaceous material in the fine dust was identified as soot, originating from the incomplete combustion of coal volatiles.

With WPI, the H₂ content and CV typically increase, whilst the amount of CO₂ decreases in the offgas. The composition of mixed waste plastics from different cities varies, and therefore the composition of the generated offgas changes. Sekine and others (2009) calculated the offgas yield, composition and CV for four plastic resins (PE, PP, PS and PET) as part of a life cycle assessment study. The plastic injection rate in each case was 50 kg/thm and the PCI rate was 139 kg/thm, that is, the waste plastics replaced some of the coke. Both the amount and CV of the offgas increased with each of the four plastic resins (*see* Table 11). The increase in the CV is because the CV of the plastics were all higher than that of the coke. Wakimoto (2001) also report that injecting mixed waste plastics increased both the yield and CV of the offgas in a test run at the Keihin BF1. However, calculations by Ziębik and Stanek (2001) indicated the reverse with PS-type plastics. As expected, raising the rate of WPI increases the amount of H₂ in the offgas (Heo and Baek, 2002).

8.2 Emissions

There is little published information on the changes in air emissions when coal and/or waste plastics are injected into a BF. Injecting coal did not cause an increase in the sulphur content of the offgas when coals averaging 0.76% sulphur were injected at the Burns Harbor steelworks in Indiana, USA (Hill and others, 2004). A life cycle inventory for BFs by Tata Steel showed that both SO₂ and NO₂ emissions actually decreased by around 22% and 16%, respectively, when the PCI rate increased from 16 to 116 kg/thm (Soni and others, 2000).

Injecting waste plastics should reduce SO₂ emissions as plastics normally have a low sulphur content or are sulphur free. This was the case at Linz, Austria, when WPI was introduced, replacing some of the heavy oil injectant and coke (denkstatt GmbH, 2007; Sigmund, 2009). Other emissions, such as NO_x, can be expected to remain about the same. Certainly, NO_x, SO_x and particulate emissions from German BFs that introduced WPI still met the statutory environmental regulations (Ziębik and Stanek, 2001). CO₂ emissions, which are lower with WPI, are discussed in Section 8.3.

Concern has been expressed that injecting chlorine-containing waste plastics, such as PVC, could lead to emissions of dioxins and furans as chlorine is usually responsible for their

Table 11 Offgas generated from different plastic resins (modified from Sekine and others, 2009)

Offgas	Without plastics	PE	PP	PS	PET
Input					
Iron ore, t	0.313	0.313	0.313	0.313	0.313
Coke, kg/thm	384.9	326.2	334.2	320.9	356.5
Pulverised coal, kg/thm	139	139	139	139	139
Sintered ore, t	1.17	1.17	1.17	1.17	1.17
Output					
Amount, m ³ /thm	1670.9	1747.3	1787.2	1684.4	1741.8
Composition, %					
CO	22.9	21.1	21.2	21.9	22.4
CO ₂	21.3	20.2	20	20.8	20.6
H ₂	4.6	7.3	7.2	6.3	5.4
H ₂ O	2.4	3.8	3.8	3.3	2.7
N ₂	48.9	47.5	47.9	47.8	48.9
CV, MJ/m ³	3.4	3.47	3.46	3.44	3.41

creation. However, measurements at the Stahlwerke Bremen found no significant differences in dioxin emissions when waste plastics were injected. Dioxin emissions with and without plastics injection were about a factor of 100 below the German TA Luft standard of 0.1 ng/m³ for waste incinerators (Janz and Weiss, 1996). The measurements were carried out on the waste gases from the hot stoves which are heated with the BF offgas. The WPI rate was limited to 35 kg/thm. The injection of 44 kg/thm of ASR (shredder light fraction) did not increase dioxins and furans emissions at EKO Stahl's (now ArcelorMittal Eisenhüttenstadt) BF6 (Korobov and others, 2003). Similarly, no dioxins or furans were detected in the offgas when coal was replaced with 10% ASR (containing 0.5% chlorine) in a pilot-scale test (Mirabile and others, 2002). The low emissions of dioxins/furans are because the high temperature in the raceway does not allow the formation of these compounds. Furthermore, the reducing atmosphere in the low temperature region at the top of the furnace prevents the regeneration of dioxins and furans (Lüngen and Theobald, 1997; Ogaki and others, 2001).

The chlorine content limitation for plastics and coal (typically to below 1.5% and 0.05%, respectively) is due to the corrosive properties of the generated chlorine compounds, in particular, hydrochloric acid (HCl). Chlorine, formed in the raceway when coal is injected, reacts with the gaseous alkalis (from the coal or coke ash) to form alkali chlorides (NaCl and KCl). Some HCl and minor amounts of other chlorine compounds are also generated (Lin and others, 2005). Injecting chlorine-containing plastics generates mostly HCl, part of which is removed by the limestone in the furnace (Ogaki and others, 2001). The alkali chlorides (also generated from the iron ore) can circulate within the shaft causing sinter disintegration and consequently, increased fines content and a deterioration in furnace permeability. The chlorine

compounds can also corrode the refractory lining and the pipelines in the offgas cleaning system. They are removed in the wash water from the scrubber.

Thermodynamics and metallurgy of the BF process concentrate the trace elements originating from waste plastics, coal, coke and iron ore into different output streams. The element flow analysis carried out by Buegler and co-workers (Buegler, 2009b; Buegler and others, 2007) over a period of three months at BF A in Linz, Austria, with a WPI rate of 35 kg/thm, was discussed in Section 7.3, in relation to hot metal quality. This section examines lead, cadmium and mercury emissions. Mercury emissions may be regulated in the future.

Cadmium and mercury emissions from BFs are lower than those from waste incinerators, although lead emissions are slightly higher (denkstatt GmbH, 2007). Most of the lead (*see* Figure 17 on page 44) comes from the iron ore (sinter, lump ore and pellets), followed by the waste plastics and coke. The majority exits the BF absorbed on the fine dust particles from the burden materials and coke, and is removed via the scrubber (over 80%). Cadmium and mercury originate in the waste plastics. Again, they are absorbed on the fine dust particles and so are removed in the scrubber – around 75% for cadmium and 90% for mercury (*see* Figure 17 on page 44). Only about 1% each of cadmium and lead, and 5% of the mercury are emitted in the gaseous metallic state. Therefore small modifications to the operation of the scrubbers will allow comparable emissions levels to BFs without plastics injection.

8.3 CO₂ emissions and abatement

CO₂ emissions from BFs are affected by a number of factors.

Smaller furnaces tend to emit more CO₂/t product than large ones due to their lower efficiency. A larger furnace is usually more efficient because the heat losses are lower and it is usually more economical to install energy efficient equipment. The energy loss for an efficient BF is <10% of the total energy input (IEA, 2007). Moreover, the quality of the raw materials influences energy consumption and hence CO₂ emissions. For instance, lower ash coals produce lower amounts of slag than higher high coals, and therefore a better thermal efficiency is achieved since less energy is required to melt the ash (Carpenter, 2006). For each percentage increase in the ash content of injected coal, about 1.5 kg/thm of extra coke is consumed (IEA, 2007), increasing the carbon input and therefore, CO₂ emissions. This figure would probably apply to mixed waste plastics as well. The ash and water content of municipal waste plastics from 7 Japanese cities was found to vary from 9.5 to 31.3% (Sekine and others, 2009), although pre-treatment of the waste plastics would reduce the ash and water contents.

Coke quality affects the amount of reducing agent (coke, coal and waste plastics) that is needed in the BF and consequently, CO₂ emissions. 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). This figure is likely to be the same for ash in the coal and waste plastics injectants. Coke quality depends on the quality of the coal used in its production and the coking process.

Ore qualities differ in their chemical composition and iron content, which affects the energy needed for the reduction reaction to produce iron, and to melt the iron ore. The chemical composition of the gangue affects the amount of limestone or lime that must be added to achieve basicity of the slag. In total these factors can make a 1–2 GJ/t difference in the energy needs for a BF (IEA, 2007). Unfortunately, the quality of iron ore is declining due to the depletion of high quality deposits. Consequently, the energy needs for ironmaking will increase in the future.

PCI reduces overall CO₂ emissions from a steelworks (compared to all-coke operation). This is principally because PCI reduces the need for coke and hence energy consumption and CO₂ emissions from the coking plant. The energy saved is on average 3.5 GJ/t coke replaced (Delgado and others, 2007). PCI can also lower energy consumption within the BF.

A life cycle assessment (LCA) evaluates the environmental performance of products and materials from mining of the raw materials through to end-of-life and waste disposal. The initial phases of a LCA involve performing a life cycle inventory, which quantifies the material, energy and emissions associated with a particular system. The iron and steel industry has complex flows of energy and materials, both inside and outside the steelworks. Most of the commodities can be sold 'over the fence' and some can be shipped long distances. Consequently, the full production energy use and CO₂ emissions may be considerably higher or lower than the site footprint would suggest (IEA, 2007). For example, buying coke and/or electricity would reduce CO₂ emissions at the site but increase the emissions elsewhere. LCA results are dependent on where the system boundaries are set.

The World Steel Association (formerly the International Iron and Steel Institute) has used a LCA approach to quantify resources use, energy and environmental emissions associated with the production of fourteen steel industry products from the extraction of raw materials through to the steel factory gate ('cradle-to gate'). The life cycle inventory included both the BF/basic oxygen furnace and electric arc furnace routes (*see* www.worldsteel.org). A life cycle inventory for BFs by Tata Steel showed around a 6.5% CO₂ reduction when the PCI rate increased from 16 kg/thm to 116 kg/thm (Soni and others, 2000).

Injecting waste plastics further lowers CO₂ emissions – by about 30% in comparison to coke and coal (Ogaki and others, 2001). This is because their higher H₂ content leads to higher H₂O emissions and less CO₂. In addition, energy consumption tends to decrease because of the lower heat demand by the direct reduction, solution loss and silicon transfer reactions. Based on the carbon content of the reducing agents, Delgado and others (2007) estimated that injecting 1 t of an average non-chlorinated thermoplastic (average 800 g C/kg) leads to a reduction of 113 kg of CO₂. WPI at the Linz works in Austria, albeit where waste plastics replace nearly 25% of the heavy oil injectant, is cutting CO₂ emissions by 400,000 t/y (voestalpine, 2007). There is a limit, though, on the amount of waste plastics that can be injected. Calculations by Asanuma and others (2000) indicated that the maximum WPI rate is 250 kg/thm for 3.1 mm sized agglomerated waste plastics (and is around 250 kg/thm for coal). However, according to the World Steel Association, an increase of coal injection above 180 kg/thm does not reduce the coke amount, and the additional coal is just gasified and produces more offgas. This is probably the case for waste plastics, as well.

LCA methodology used by Narita and others (2001) estimated the CO₂ reduction effects of PCI and WPI to be 0.07 and 0.16 kg CO₂, respectively, at an injection rate of 0.1 kg/kg of hot metal. A LCA study by Inaba and others (2005), quoted by Sekine and others (2009), showed that the CO₂ reduction potential for waste plastics is dependent on whether they replace the coke or pulverised coal.

Since the composition of the mixed waste plastics affects CO₂ emissions, Sekine and others (2009) calculated the reduction potential of CO₂ emissions when PE, PP, PS and PET are injected into BFs, and hence those from municipal waste plastics consisting of these materials. PVC was excluded since it is removed in the plastics pretreatment process. The life cycle inventory analysis was conducted following ISO14040 procedures. The system boundary included the pretreatment of the waste plastics, the processes within the steelworks that are affected by waste plastics usage (such as the coke oven and BF), and the associated power plant (where the surplus gas is utilised). The Rist model was applied to calculate changes in the energy and material inputs and outputs of a BF when the waste plastics are used as a coke substitute. In each case the plastics injection rate was 50 kg/thm and the PCI rate was 139 kg/thm. PE had the largest potential for reducing CO₂ emissions, followed by PS and then PP (*see* Figure 18). PET, however, increased CO₂ emissions, which was attributed to its relatively low CV and carbon and hydrogen contents (compared to coke), leading to

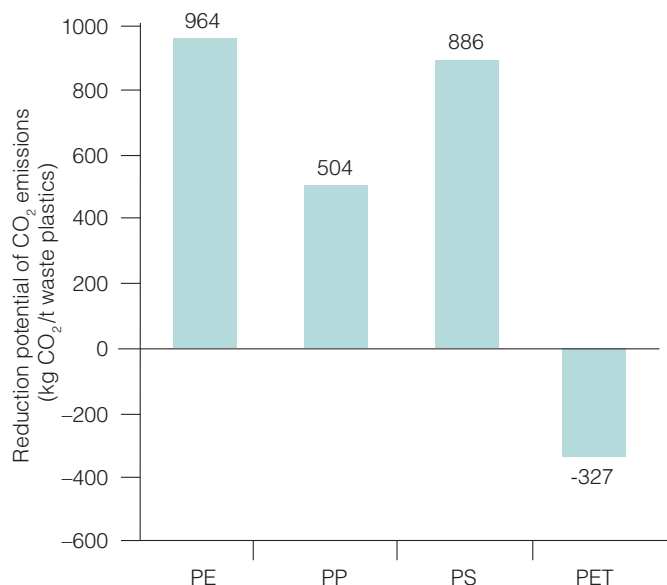


Figure 18 Reduction potential of CO₂ emissions with 1 t waste plastics injection (Sekine and others, 2009)

a relatively small coke substitution effect. Overall, the reduction potential of CO₂ emissions for seven Japanese cites ranged from 398 kg to 580 kg CO₂/t of injected municipal waste plastics. The difference is mainly due to the amount of impurities (ash, water) in the waste plastics. It should be noted that the Rist model calculations indicate the ideal potential for reducing CO₂ emissions. The actual reduction effect when waste plastics are injected is dependent on the BF operating conditions.

These studies all show that injecting H₂-containing reducing agents, such as coal and waste plastics, can lower CO₂ emissions (compared to all-coke operation; the H₂ content of coke is only around 0.5%). Further CO₂ reductions can be achieved by lowering the carbon input (coke, coal and waste plastics). Measures to accomplish this can be divided into two groups (Anyashiki and others, 2007), those that promote:

- higher efficiency BF operation. These include higher blast temperatures, improved shaft efficiency, and a lower thermal reserve zone temperature. However, these measures also reduce the supply of offgas to downstream processes. Minimisation of offgas production reduces CO₂ emissions but may not be possible at plants where utilisation of the offgas in downstream processes is important, for instance, to ensure the power supply to other works areas or for external users; and
- energy savings in the ironmaking process, such as the reduction of BF heat loss, charging of metallic iron, lower slag rate, and operating with a lower sinter ratio or pre-reduced sinter.

Furthermore, recycling the decarbonised offgas to the BF lowers CO₂ emissions (Murai and others, 2004; Yagi and others, 2006). This technology, commonly termed top gas recycling, first removes the CO₂ by a commercial process such as Selexol, before reheating and injecting the offgas into the furnace shaft and/or through the tuyeres. It requires operating the furnace with a pure O₂ blast to avoid nitrogen accumulation due to recycling. The captured CO₂ can be

stored underground. The offgas, which principally consists of CO and H₂, reduces carbon consumption and increases furnace productivity. One organisation pioneering this technology is ULCOS (Ultra-Low CO₂ Steelmaking), a consortium of 48 European companies and organisations (*see* www.ulcos.org). Pilot-scale testing of the technology over a 6 week period resulted in up to a 76% reduction in CO₂ emissions, provided the captured CO₂ is stored (Danloy and others, 2009).

8.4 Waste water and by-products

Steel production is a water intensive process, consuming around 180–200 m³ water/t steel. BFs consume around 14 to 17.5 m³ water/thm (Johnson, 2003), the majority of which is used for cooling purposes – to cool the BF walls and tuyeres, and to quench the slag. Water is additionally utilised in the offgas cleaning system. Waste water generated from these processes is treated before it is recycled; over 90% of the water is recycled.

There is little published information on the changes in the amount and composition of the waste water produced when waste plastics are injected into BFs, although no significant difference from their use is expected. Around 0.1–3.5 m³ of waste water/thm is generated and therefore, injecting 1 t of waste plastics would lead to the production of 0.2–7 m³ waste water (Delgado and others, 2007). The amount and composition of the waste water partly depends on the quality of the BF raw materials. For instance, high salt raw materials can require significantly higher volumes of wash water in the offgas scrubbing system. An element flow analysis carried out at the BF A in Linz, Austria, by Buegler and others (2007) found that the majority of the cadmium from the waste plastics ended up in the scrubber waste water and the solids from the scrubber (*see* Figure 17 on page 44). Water treatment process can remove cadmium and other heavy metals in the waste water before it is recycled or discharged.

Integrated iron and steel production results in about 450–500 kg of residues and by-products per tonne of crude steel produced. Of this, more than 375 kg/t is slag and some 60–65 kg/t is dust and sludge from flue gas cleaning and scale. Around 86% of all residues and by-products can be recycled internally and externally, after treatment (Working Group on Strategies and Review, 2001). The coarse dust removed from the BF offgas by dry separation can be recycled internally. The sludge containing the finer particles from the offgas treatment system is typically landfilled.

Different forms of slag are produced depending on the method used to cool the molten slag. These include air cooled slag, expanded or foamed slag, pelletised slag and granulated slag. The majority of the slag can be sold, with only a small amount being landfilled (<10%). Thus BF slag is considered to be a by-product rather than a waste. The slag can be utilised in road construction, cement production, as a building material and for special purposes. The possible uses depend on the properties and form of the slag.

The composition of the slag depends on the quality of the BF

raw materials. It is formed from the gangue material in the iron ore, and the ash from the coke, coal and waste plastics. It consists principally of silicates and aluminosilicates of calcium and magnesium, together with other compounds of sulphur, iron, manganese and other trace elements. There is little published information on changes in the amount and composition of slag with the co-injection of coal and waste plastics. Certainly the amount of slag generated will increase with rising injection rates and increasing ash and sulphur contents of these reductants. Test injections in South Korea showed higher slag rates when PBT and PE were injected (Heo and others, 2000b).

Sulphur in the slag originates mainly from the coal, with some coming from the waste plastics. However, the sulphur is effectively encapsulated within the slag. It is only any sulphur present on the surface that is potentially leachable (Waste and Resources Action Programme, 2007). The trace elements will also probably be encapsulated within the slag. Injecting waste plastics may adversely affect the quality of the slag, but probably not enough to influence its utilisation.

9 Conclusions

PCI is a well established technology practised in most, if not all, countries operating coke-based BFs. Coal typically costs less than natural gas and oil, and its supplies are more stable. The injection of waste plastics, either as a separate injectant or co-injected with coal, is practised only in a few BFs in Japan and Europe. A factor restricting the utilisation of waste plastics is the cost of their collection and treatment. BF operators need a reliable supply of consistent quantity and quality, and at a suitable cost. This requires an effective and efficient collection system for obtaining waste plastics from the widely distributed waste streams coming from households, industry and agriculture.

The amount of waste plastics available for recycling is likely to increase in countries where there are landfill shortages and where legislation restricting the amount of wastes that can be landfilled are being, or have been, introduced. These include the member states of the European Union, where new waste treatment plants are opening up, capable of supplying waste plastics of sufficient quality to BFs. Both the BFs in Linz, Austria, and Salzgitter, Germany, which recently started to inject waste plastics, are sourcing the material from waste treatment plants not owned by them. This compares to the situation in Japan where commercial injection of waste plastics began in 1996. Here the waste plastics are treated on site by the steel company (or a subsidiary company).

The substitution of coke by the coal and waste plastic injectants is limited to a maximum of around 40% since the injectants are unable to give the physical support for iron ore provided by coke. For stable operation, the maximum PCI/WPI rate is around 250 kg/thm. But according to the World Steel Association, an increase of coal injection above 180 kg/thm does not reduce the coke amount. The additional coal is just gasified to produce more offgas. This is probably the case for waste plastics as well. These high injection rates require changes in operating parameters and the use of more expensive higher quality coke.

The composition and properties of the injectants influence the operation, stability and productivity of a BF, the quality of the hot metal product, and the offgas composition. The choice of injectant is plant specific due to differences in BF design and operating conditions. Selecting coals for injection is a complicated process that often involves compromises. In general, coals with less ash, moisture, sulphur and alkali are favoured. For mixed waste plastics, low chlorine, moisture, ash and sulphur contents are preferred. Most types of coal and waste plastics can be utilised at low injection rates. However, as injection rates increase more complex characteristics, such as combustibility, char reactivity and flow properties, influence their selection.

Standard tests for evaluating coal and waste plastics need to be developed that reflect conditions occurring in the BF. For instance, no standard test yet exists for determining the reactivity of coals or waste plastics and their chars to CO₂ under BF conditions. There is 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 small (milligram or gram sized) samples used in bench-scale tests can provide a truly representative sample of the tonnes of injectant consumed in the furnace.

Computer models offer a way of assessing the behaviour and impact of injectants in the BF and their effect on the quality of the hot metal product. But the validity of these models has been questioned because the mechanisms they are portraying are complex and not fully understood. Their accuracy is dependent on the assumptions made and the validity of relationships built into the models. As the models become more widely validated in BFs, they should become more useful. However, it may never be possible to forecast the behaviour of different coal and waste plastic injectants with absolute certainty.

Pulverised coal (75 µm) and waste plastics (<10 mm) currently have separate transport and injection systems due to the large difference in their particle size. Coal-plastic blends are potentially an economic means to get finely ground plastics into the BF without the need for expensive separate injection systems. This would, however, increase the plastic preparation costs since they would need to be ground to around the same size as the pulverised coal. JFE Steel has developed a new preparation process that produces 200–400 µm sized waste plastics that has recently been introduced at its East Japan Works.

The reliability of the transport and injection system is crucial at high injection rates since any interruption can quickly lead to serious problems. The equal distribution of the injectants through the tuyeres is also fundamental. Blockages in the transfer pipelines have been attributed to the moisture and clay minerals in coal, and the presence of ultrafine particles. The moisture content of waste plastics is also controlled to prevent blockages. Lances still frequently clog and so there are set procedures for detecting and clearing these blockages before they can cause any damage. A standardised, simple and practical test is needed to assess the flowability and handleability of pulverised coals and their blends, and of waste plastics to enable problematic materials to be identified before they are utilised.

The combustibility of the injectants is important because of their effect on furnace permeability. Utilising injectants with a high burnout and optimising operating conditions, such as blast temperature and oxygen enrichment, can improve combustion efficiency. HV coals generally produce more reactive chars than LV ones, are easier to convey, but give a lower coke replacement ratio. They can also lead to higher soot formation (from unburnt volatiles) and consequent problems in the gas cleaning systems. But char reactivity may not be very significant at high injection rates because of the short residence time (10–50 ms) in the raceway and, at the high raceway temperatures, 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. The combustion efficiency of waste plastics is influenced by their particle size and strength. Harder and stronger particles, made by grinding solid plastics, can have a higher combustion efficiency than softer particles, made from film-like plastics. This is because of their longer residence time in the raceway. Softer agglomerated particles tend to fragment due to thermal shock when they enter the raceway, and the resultant fine particles exit the raceway before they are fully combusted.

The combustibility of LV coals can be enhanced by blending with HV coals. The HV coal releases more volatile matter helping to form a higher gas temperature field, which then heats up the LV coal. This promotes its devolatilisation, ignition and combustion. The synergistic effect is more pronounced the higher the fraction of HV coal, up to a certain percentage. But the combustion performance of a blend is more complex to predict than that of a single coal. Preferential grinding of the softer coal in the blend can occur, influencing the mineral and petrographic composition of the resultant particles, and the subsequent combustion behaviour. Each of the coal blend components devolatilises and combusts at different temperatures and at different times, and their burnout could therefore vary considerably. In addition, interactions between the component coals can occur, complicating predictions of the blend's combustion behaviour. Injecting waste plastics as well, further complicates the matter since they can interact with the coal and compete for oxygen.

Interactions between coal and wastes plastics can be exploited to improve their overall combustion efficiency. JFE, for instance, achieved this by co-injecting the materials through the same lance, causing the smaller coal (75 μm) particles to adhere to the surface of the larger plastic particle (3 mm). This resulted in the generated heat from the combustion of coal being supplied directly to the plastic particles, accelerating their combustion. Furthermore, the residence time of the coal in the high temperature area is prolonged, improving its combustibility. The coal and waste plastics are mixed in the piping just before the injection lance to avoid potential blockage problems.

The consumption of unburnt char outside the raceway is a major factor influencing the injectant rate. Operating experience has shown that, in a well-balanced furnace, most of the unburnt char exiting the raceway is consumed within the furnace via gasification with carbon dioxide and steam, carburisation of the molten iron, and slag reactions. Research, though, is still needed to identify the fundamental factors contributing to char gasification and its assimilation in the slag and hot metal.

An undesirable consequence of PCI/WPI is the transfer of contaminants to the hot metal since this can adversely affect the hot metal quality, adding to the refining costs in the steel shop. Of concern for coal is its silicon and sulphur contents, although the main source of silicon is the iron ore. Sulphur, to a lesser extent, can also originate from the waste plastics. Thus low sulphur injectants (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 adding fluxes 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. Non-ferrous metals in automobile shredder residues can also end up in the hot metal, which is difficult to rectify at a later stage. Treatment processes have been developed to minimise the content of these elements in automotive shredder residues.

PCI/WPI reduces the overall CO₂ emissions from the ironmaking process. PCI decreases the need for coke and hence energy consumption and CO₂ emissions from the coking plant. Injecting waste plastics further lowers CO₂ emissions (by about 30% in comparison to the use of coke and/or coal) due to their higher hydrogen content. There is less CO₂ produced from the combustion and reduction processes, and a lower heat demand by the direct reduction, solution loss and silicon transfer reactions. Small modifications to the offgas scrubbers keep emission levels comparable to operation without plastics. Concerns over emissions of dioxins and furans have proved groundless since they are negligible.

Injecting coal and waste plastics can help BF operators to maximise productivity, whilst reducing costs and minimising environmental impacts. Replacing coke with cheaper coal and waste plastics reduces operating costs and lowers CO₂ emissions. With their higher utilisation efficiency (around 80%), waste plastics can be employed more efficiently in BFs than in plants which directly combust these materials to generate heat or electricity. Moreover, with the increasing amounts of waste plastics being generated, there is potentially a large market for appropriately treated waste plastics of which BF operators can take advantage.

10 References

- Akiyama T, Kajiwara Y (2000)** Generation of fine in blast furnace at high rate PCI. In: *Advanced pulverized coal injection technology and blast furnace operation*. Oxford, UK, Pergamon - Elsevier Science, pp 169-215 (2000)
- Al-Salem S M, Lettieri P, Baeyens J (2010)** The valorization of plastic solid waste (PSW) by primary to quaternary routes: from re-use to energy and chemicals. *Progress in Energy and Combustion Science*; **36**(1); 103-129 (Feb 2010)
- Anyashiki T, Shimoyama I, Fujimoto H, Watakabe S, Sato T, Takeda K (2007)** Recent development in ironmaking technology toward reduction in CO₂ emission. In: *METEC InSteelCon 2007, proceedings, 3rd international steel conference on new developments in metallurgical process technologies*, Düsseldorf, Germany, 11-15 Jun 2007. Düsseldorf, Germany, Stahlinstitut VDEh, pp 314-321 (2007)
- Asanuma M, Ariyama T, Sato M, Murai R, Nonaka T, Okochi I, Tsukiji H, Nemoto K (2000)** Development of waste plastics injection process in blast furnace. *ISIJ International*; **40**(3); 244-251 (2000)
- Asanuma M, Ariyama T, Iemoto M, Wakamatsu S, Masuko S, Suyama K (2001)** Verification of PVC dechlorination process based on 1,000 t/y semi-commercial plant operation. *Kagaku Kogaku Ronbunshu*; **27**(3); 326-334 (2001) (In Japanese)
- Asanuma M, Kajioaka M, Kuwabara M, Fukumoto Y, Terada K (2009)** Establishment of advanced recycling technology for waste plastics in blast furnace. *JFE Technical Report*; (13); 34-40 (May 2009)
- Assis P S, Sobrinho P J N, Vieira C B, Tenório J A (1999)** Some thoughts about injection of plastics into the blast furnace. In: *ICARISM '99, proceedings of the international conference on alternative routes of iron and steelmaking*, Perth, WA, Australia, 15-17 Sep 1999. Publications series no. 3/99, Carlton, Vic, Australia, Australasian Institute of Mining and Metallurgy, pp 240-241 (1999)
- Babich A, Gudenau H W, Senk D, Formoso A, Menendez J L, Kochura V (2002)** Experimental modelling and measurements in the raceway when injecting auxiliary substances. Paper presented at: *International blast furnace lower zone symposium*, Wollongong, NSW, Australia, 25-27 Nov 2002. 14 pp (2002)
- Babich A, Gudenau H W, Senk D (2003)** Optimisation of energy consumption in ironmaking processes by combined use of coal, dust and waste. In: *Proceedings, 3rd international conference on science and technology of ironmaking: METEC 03*, Düsseldorf, Germany, 16-20 Jun 2003. Düsseldorf, Germany, Stahlinstitut VDEh, pp 89-94 (2003)
- Baosteel (2008)** *Sustainability report 2007*. Shanghai, China, Baosteel Iron & Steel Co Ltd, 116 pp (2008)
- Bennett P (2004)** *Predicting pulveriser performance*. ACARP Report C13062, Brisbane, Qld, Australia, Australian Coal Association Research Program (ACARP), vp (Jul 2004)
- Bennett P (2007)** *PCI - impact on blast furnace operation*. ACARP Report C15069, Brisbane, Qld, Australia, Australian Coal Association Research Program (ACARP), 45 pp (Mar 2007)
- Borrego A G, Osório E, Casal M D, Vilela A C F (2008)** Coal char combustion under a CO₂-rich atmosphere: implications for pulverized coal injection in a blast furnace. *Fuel Processing Technology*; **89**(11); 1017-1024 (Nov 2008)
- Buchwalder J, Fuchs T, Hunger J, Siepert T (2003)** Experience with using alternative reducing agents at blast furnace. *Revue de Métallurgie - Cahiers d'Informations Techniques*; **100**(3); 289-295 (Mar 2003)
- Burgler T (2009a)** Linz, Austria, voestalpine Stahl, Ironmaking Department, *personal communication* (2009)
- Burgler T (2009b)** Challenges of waste management at international scale. Presentation at: *5th WISE course*, Linz, Austria, 10-15 May 2009. 29 pp (2009)
- Burgler T, Brunnbauer G, Pillmair G, Ferstl A (2007)** Waste plastics as reducing agent in the blast furnace process - synergies between industrial production and waste management processes. In: *METEC InSteelCon 2007, proceedings, 3rd international steel conference on new developments in metallurgical process technologies*, Düsseldorf, Germany, 11-15 Jun 2007. Düsseldorf, Germany, Stahlinstitut VDEh, pp 1037-1043 (2007)
- Cao F, Long S, Luo, Z (2005)** The combustion efficiencies of the waste plastics as supplemental fuel for blast furnace. *Steel Research International*; **76**(10); 690-694 (Oct 2005)
- Carpenter A M (1995)** *Coal blending for power stations*. IEACR/81, London, UK, IEA Clean Coal Centre, 83 pp (Jul 1995)
- Carpenter A M (2002)** *Coal quality assessment – the validity of empirical tests*. CCC/63, London, UK, IEA Clean Coal Centre, 100 pp (Sep 2002)
- Carpenter A M (2006)** *Use of PCI in blast furnaces*. CCC/116, London, UK, IEA Clean Coal Centre, 66 pp (Sep 2006)
- Chen W-H, Du S-W, Yang T-H (2007)** Volatile release and particle formation characteristics of injected pulverized coal in blast furnaces. *Energy Conversion and Management*; **48**(7); 2025-2033 (Jul 2007)
- Danloy G, Berthelemot A, Grant M (and others) (2009)** ULCOS - pilot testing of the low-CO₂ blast furnace process at the experimental BF in Luleå. *Revue de Métallurgie - Cahiers d'Informations Techniques*; **106**(1); 1-8 (Jan 2009)
- Defendi G -A, Fujihara F -K, Correa M, Cruz R, Rezende R, Osorio E, Parreiras R (2008)** Development of knowledge on combustion and ash behavior of pulverized coals injected in ArcelorMittal Tubarão blast furnaces. *Revue de Métallurgie - Cahiers d'Informations Techniques*; **105**(7/8); 346-355 (Jul-Aug 2008)
- Delgado C, Barruetaña L, Salas O, Wolf O (ed) (2007)** *Assessment of the environmental advantages and drawbacks of existing and emerging polymers recovery processes*. EUR 22939, Luxembourg, Office for Official Publications of the European Communities, 286 pp (2007)
- denkstatt GmbH (2007)** Plastic (packaging) waste management in Austria - challenges and latest strategies. Paper presented at: *EPRO - European Association of Plastic Recycling and Recovery Organisations meeting*, Paris, France, Jun 2007, 25 pp (2007)

- Deno T (2000)** Upper limit of PCR. In: *Advanced pulverized coal injection technology and blast furnace operation*. Oxford, UK, Pergamon - Elsevier Science, pp 259-298 (2000)
- Ecker A (2008)** Everything depends on the right balance. Integrated plastics waste management system - Austria. *Recycling M@gazine*; (10); 6-11 (2008)
- Fischer T (2006)** Getting a return from residue. *Scrap*; 57-62 (May/June 2006)
- Gao L, Wu L, Paterson N, Dugwell D, Kandiyoti R (2008)** The use of wire mesh reactors to characterise solid fuels and provide improved understanding of larger scale thermochemical processes. *International Journal of Oil, Gas and Coal Technology*; 1(1/2); 152-178 (2008)
- Garcia A (1999)** Development of coal injection technology at Aceralia's blast furnaces. In: *6th Americas coal conference*, Cartagena, Colombia, 19-21 Apr 1999. London, UK, Coaltrans Conferences Ltd, pp 85-102 (1999)
- Geerdes M, Toxopeus H, van der Vliet C (2004)** *Modern blast furnace ironmaking: an introduction*. Düsseldorf, Germany, Stahleisen GmbH, 126 pp (2004)
- Gomes M L I, Osório E, Vilela A C F (2006)** Thermal analysis evaluation of the reactivity of coal mixtures for injection in the blast furnace. *Materials Research*; 9(1); 91-95 (Jan/Mar 2006)
- Goto A, Morozumi Y, Hagiya H, Aoki H, Miura T (2008)** Numerical investigation of waste plastic injection in a blast furnace. *Journal of Chemical Engineering of Japan*; 41(3); 182-193 (2008)
- GUA (2005)** *Recycling definitions aiming at a maximum of environmental benefits*. Vienna, Austria, GUA - Gesellschaft für umfassende Analysen GmbH, 6 pp (2005)
- Gudenau H W, Senk D, Fukada K, Babich A, Froehling C, García L L, Formoso A, Alguacil F J, Cores A (2003)** Coke, char and organic waste behaviour in the blast furnace with high injection rate. *Revista de Metalurgia (Madrid)*; 39(5); 367-377 (Sep-Oct 2003)
- Gupta S, Sahajwalla V, Wood J (2006)** Simultaneous combustion of waste plastics with coal for pulverized coal injection application. *Energy and Fuels*; 20(6); 2557-2563 (Nov-Dec 2006)
- Gupta S, French D, Sakurovs R, Grigore M, Sun H, Cham T, Hilding T, Hallin M, Lindblom B, Sahajwalla V (2008)** Minerals and iron-making reactions in blast furnaces. *Progress in Energy and Combustion Science*; 34(2); 155-197 (Apr 2008)
- Heo Nam-Hwan, Baek Chan-Yeong (2002)** The effect of injection of waste plastics on the blast furnace operation. *Geosystem Engineering*; 5(1); 1-4 (Mar 2002)
- Heo Nam-Hwan, Baek Chan-Yeong, Yim Chang-Hee (2000a)** Thermal decomposition and combustion behavior of plastics in blast furnace. *Journal of the Korean Institute of Resources Recycling*; 9(6); 15-22 (Dec 2000) (In Korean)
- Heo Nam-Hwan, Baek Chan-Yeong, Yim Chang-Hee (2000b)** Analysis of furnace conditions with waste plastics injection into blast furnace. *Journal of the Korean Institute of Resources Recycling*; 9(6); 23-30 (Dec 2000) (In Korean)
- Hill D G, Makovsky L E, Sarkus T A, McIlvried H G (2004)** Blast furnace granular coal injection at Bethlehem Steel's Burn Harbor plant. *Mineral Processing & Extractive Metallurgy Review*; 25(1); 49-65 (2004)
- Hotta H (2003)** Recycling technologies for promoting recycling-oriented society. *NKK Technical Review*; (88); 160-166 (2003)
- Hutchinson S (2001)** Blast furnace operating experience with pulverized coal injection. In: *Coke summit 2001*, Pittsburgh, PA, USA, 15-17 Oct 2001. Portland, ME, USA, Intertech, Paper 24, 18 pp (2001)
- Hutny W P, Giroux L, MacPhee A, Price J T (1996)** Quality of coal for blast furnace injection. In: *Proceedings, Blast furnace injection symposium*, Cleveland, OH, USA, 10-12 Nov 1996. Pittsburgh, PA, USA, Association of Iron and Steel Engineers, pp 1-31 (1996)
- Hutny W P, Giroux L, Price J T, MacPhee A, McIntyre A (1997)** Effect of injected coal properties on performance of the blast furnace. In: *Proceedings of the 9th international conference on coal science: ICCS '97*, Essen, Germany, 7-12 Sep 1997. DGMK Tagungsbericht 9703, Hamburg, Germany, Deutsche Wissenschaftliche Gesellschaft für Erdöl, Erdgas und Kohle eV, vol II, pp 1315-1318 (1997)
- Hyde J B, Hutchinson S, Brown R (1996)** Start-up of the PCI facility at Stelco Hilton Works. In: *Proceedings, blast furnace injection symposium*, Cleveland OH, USA, 10-12 Nov 1996. Pittsburgh, PA, USA, Association of Iron and Steel Engineers, pp 197-209 (1996)
- Ida H (2006)** Current status of plastics recycling in Japan. Paper presented at: *Feedstock substitutes, energy efficient technology and CO₂ reduction for petrochemical products workshop*, Paris, France, 12-13 Dec 2009. Available at: www.iea.org/Textbase/work/2006/petrochemicals/Ida_Plastics_Recycling_Japan.pdf Paris, France, IEA, 29 pp (Dec 2006)
- IEA (2007)** *Tracking industrial energy efficiency and CO₂ emissions*. Paris, France, OECD/IEA, 324 pp (2007)
- IEA (2009)** *Coal information 2009 with 2008 data*. Paris, France, OECD/IEA, vp (2009)
- Inaba R, Hashimoto S, Moriguchi Y (2005)** Life cycle assessment of recycling in the steel industry for plastic containers and packaging. Influence of system boundary. *Journal of the Japan Society of Waste Management Experts*; 16(6); 467-480 (2005) (In Japanese)
- Jaffarullah R, Ghosh B K (2005)** Alternate fuels in blast furnaces to reduce coke consumption. *Journal of the Institution of Engineers (India). Metallurgy and Material Science Division*; 86(1); 16-23 (Apr 2005)
- Janhsen U, Günbati A, Sautner C (and others) (2007)** *Changes in the microstructure of coke while passing the blast furnace with respect to the quality of the charged coke and the behaviour of nut coke in the blast furnace*. EUR 22439, Luxembourg, Office for Official Publications of the European Communities, 193 pp (2007)
- Janz J, Weiss W (1996)** Injection of waste plastics into the blast furnace of Stahlwerke Bremen. *Revue de Métallurgie*; 93(10); 1219-1226 (Oct 1996)
- Japan Plastics Industry Federation (2006)** *Recent status of waste plastics recycling in Japan*. Available at: www.cipad.org/files/files/Waste_plastics_recycling_in_Japan.pdf Toronto, CA, Canada, Council of International Plastics Association Directors, 37 pp (2006)
- Jody B J, Daniels E J (2006)** *End-of-life vehicle recycling: the state of the art of resource recovery from shredder residue*. Report ANL/ESD/07-8, Argonne, IL, USA, Argonne National Laboratory, 146 pp (2006)
- Johnson R (2003)** Water use in industries of the future: steel industry. Section from *Industrial water management: a*

- systems approach*, Indianapolis, IN, USA, Wiley. Available at: www.ana.gov.br/Destaque/d179-docs/PublicacoesEspecificas/Metalurgia/Steel_water_use.pdf 10 pp (2003)
- Jordan C, Harasek M, Maier C, Winter F, Aichinger G, Feilmayr C, Schuster S (2008)** Simulation of plastic particles injection into the raceway of a blast furnace. In: *AISTech 2008, proceedings of the iron and steel technology conference*, Pittsburgh, PA, USA, 5-8 May 2008. Warrendale, PA, USA, Association for Iron and Steel Technology (AIST), vol 1, pp 473-482 (2008)
- Juniper L (2000)** *Thermal coal technology. A manual for Australian coal*. Brisbane, Qld, Australia, Department of Mines and Energy, QTHERM Program, 186 pp (2000)
- Kalkreuth W, Borrego A G, Alvarez D, Menendez R, Osório E, Ribas M, Vilela A, Cardozo Alves T (2005)** Exploring the possibilities of using Brazilian subbituminous coals for blast furnace pulverized fuel injection. *Fuel*; **84**(6); 763-772 (Apr 2005)
- Kamijou T, Shimizu M (2000)** PC combustion in blast furnace. In: *Advanced pulverized coal injection technology and blast furnace operation*. Oxford, UK, Pergamon - Elsevier Science, pp 63-82 (2000)
- Kim D, Shin S, Sohn S, Choi J, Ban B (2002)** Waste plastics as supplemental fuel in the blast furnace process: improving combustion efficiencies. *Journal of Hazardous Materials*; **B94**(3); 213-222 (14 Oct 2002)
- Kobe Steel (2007)** *Environmental management sustainability report 2007*. Available at: www.kobelco.co.jp/english/environment/2007/1179081_5837.html Kobe, Japan, Kobe Steel, vp (2007)
- Korobov D, Yusfin Y S, Janke D (2003)** Thermodynamic modelling of the injection of waste products into a blast furnace. *Steel Research International*; **74**(7); 403-412 (Jul 2003)
- Kruse R J, Chaubal P C, Moore J B, Valia H S (2003)** Blast furnace PCI coal selection at Ispat Inland. In: *Iron and Steel Society's international technology conference and exposition: ISSTech 2003*, Indianapolis, IN, USA, 27-30 Apr 2003. Warrendale, PA, USA, Iron and Steel Society, pp 787-797 (2003)
- Kumar A, Mukherjee T (2004)** Lowering energy consumption in ironmaking. *Tata Search*; **1**; 109-115 (2004)
- Lectard E, Hess E, Lin R (2003)** Behavior of chlorine and alkalis in the blast furnace and effect on sinter properties during reduction. In: *Proceedings, METEC congress 03, 3rd international conference on science and technology of ironmaking*, Düsseldorf, Germany, 16-20 Jun 2003. Düsseldorf, Germany, Stahlinstitut VDEh, pp 521-526 (2003)
- Lee Y S, Min D J, Jung S M, Yi S H (2004)** Influence of basicity and FeO content on viscosity of blast furnace type slags containing FeO. *ISIJ International*; **44**(8); 1283-1290 (2004)
- Lherbier L W, Serrano E J (2009)** Quality criteria for blast-furnace injection coals. In: *The challenges of coal injection in today's blast furnaces, 36th McMaster University symposium on iron and steelmaking*, Hamilton, ON, Canada, 23-25 Sep 2008. Hamilton, ON, Canada, McMaster University, pp 175-188 (2009)
- Li J, Wang H, Jin H (2007)** Combustion characteristics of coal and waste plastics blends. In: *2007 international conference on coal science and technology. Programme and full papers*, Nottingham, UK, 28-31 Aug 2007. London, UK, IEA Clean Coal Centre, CD-ROM, paper 8A5.pdf, 12 pp (2007)
- Lin R, Hartig W, Hochhaus J (2005)** Investigation of chlorine and alkali impacts on the blast furnace operation. In: *5th European coke and ironmaking congress, Proceedings*, Stockholm, Sweden, 12-15 Jun 2005. Jernkontoret, Stockholm, Sweden, vol 1, Tu4:1/1-Tu4:1/14 (2005)
- Long S, Cao F, Wang S, Sun L, Pang J, Sun Y (2006)** Study on combustion characteristic of waste plastic particle and coal powder at the blast temperature of blast furnace. In: *Proceedings, 4th international congress on the science and technology of ironmaking (ICSTI '06)*, Osaka, Japan, 26-30 Nov 2006. Tokyo, Japan, Iron and Steel Institute of Japan, pp 581-584 (2006)
- Long S, Cao F, Wang S, Sun L, Pang J, Sun Y (2008)** Combustion characteristics of polyethylene and coal powder at high temperature. *International Journal of Iron and Steel Research*; **15**(1); 6-9 (2008)
- Lu L, Sahajwalla V, Harris D (2001)** Coal char reactivity and structural evolution during combustion - factors influencing blast furnace pulverized coal injection operation. *Metallurgical and Materials Transactions B*; **32B**(5); 811-820 (Oct 2001)
- Lu L, Sahajwalla V, Kong C, McLean A (2002)** Chemical structure of chars prepared under conditions prevailing in the blast furnace PCI operation. *ISIJ International*; **42**(8); 816-825 (2002)
- Lüngen H B, Theobald W (1997)** Aspects of granulated plastics injection into blast furnaces in Germany. In: *ENCOSTEEL, steel for sustainable development, conference papers*, Stockholm, Sweden, 16-17 Jun 1997. Brussels, Belgium, International Iron and Steel Institute, pp 77-93 (1997)
- Maldonado D, Austin P R, Zulli P, Guo B (2008)** Modelling coal combustion behaviour in an ironmaking blast furnace raceway - model development and applications. In: *AISTech 2008, proceedings of the iron and steel technology conference*, Pittsburgh, PA, USA, 5-8 May 2008. Warrendale, PA, USA, Association for Iron and Steel Technology (AIST), vol 1, pp 331-344 (2008)
- Mathieson J G, Truelove J S, Rogers H (2005)** Toward an understanding of coal combustion in blast furnace tuyere injection. *Fuel*; **84**(10); 1229-1237 (Jul 2005)
- McCarthy F, Sahajwalla V, Hart J (2002)** Metal/char interactions during pulverised coal injection in a blast furnace. In: *61st ironmaking conference, proceedings*, Nashville, TN, USA, 10-13 Mar 2002. Warrendale, PA, USA, Iron & Steel Society, pp 313-324 (2002)
- Mehta A S, Sahajwalla V (2000)** Influence of composition of slag and carbonaceous materials on the wettability at the slag/carbon interface during pulverised coal injection in a blast furnace. *Scandinavian Journal of Metallurgy*; **29**(1); 17-29 (Feb 2000)
- Mehta A S, Sahajwalla V (2001)** Influence of temperature on the wettability at the slag/carbon interface during pulverised coal injection in a blast furnace. *Scandinavian Journal of Metallurgy*; **30**(6); 370-378 (Dec 2001)
- Mehta A S, Sahajwalla V (2003)** Coal-char/slag interactions during pulverised coal injection in a blast furnace: reaction kinetics and wetting investigations. *ISIJ International*; **43**(10); 1512-1518 (2003)

- Mehta A S, Sahajwalla V, Wall T F (1998)** Investigation on the modes of consumption of residual char by the slag phase during pulverised coal injection in blast furnace. In: *Proceedings, 2nd international congress on the science and technology of ironmaking and 57th ironmaking conference*, Toronto, ON, Canada, 22-25 Mar 1998. Warrendale, PA, USA, Iron and Steel Society, pp 1867-1879 (1998)
- Menad N (2007)** Recycling of auto shredder residue. *Journal of Hazardous Materials*; **139**(3); 481-490 (Jan 2007)
- Méndez L B, Borrego A G, Martínez-Tarazona M R, Menéndez R (2003)** Influence of petrographic and mineral matter composition of coal particles on their combustion reactivity. *Fuel*; **82**(15/17); 1875-1882 (Oct-Dec 2003)
- Menéndez R, Alvarez D, Fuertes A B, Hamburg G, Vleeskens J (1994)** Effects of clay minerals on char texture and combustion. *Energy & Fuels*; **8**(5); 1007-1015 (Sep-Oct 1994)
- Mirabile D, Pistelli M I, Marchesini M, Falciani R, Chiappelli L (2002)** Thermal valorisation of automobile shredder residue: injection in blast furnace. *Waste Management*; **22**(8); 841-851 (Dec 2002)
- Mitterbauer H, Buerigler T (2009)** The industry has closed the recycling loops for ELV - an example for BAT in shredder residues treatment from Austria. Presentation at: *9th international automobile recycling congress*, Munich, Germany, 11-13 Mar 2009. 19 pp (2009)
- Morgan D J, Köstera M, Haas J, van der Kamp W L (1999)** Blast furnace combustion of plastic fuel blends. In: *JOULE III programme. Clean coal technology R & D. Advanced combustion and gasification of fuel blends. Volume II. Fuel blends and alkali diagnostics*. EUR—19285/II, Brussels, Belgium, European Commission, Clean Coal Technology R & D, pp 375-400 (1999)
- Murai R, Sato M, Ariyama T (2004)** Design of innovative blast furnace for minimizing CO₂ emission based on optimization of solid fuel injection and top gas recycling. *ISIJ International*; **44**(12); 2168-2177 (2004)
- Narita N, Sagisaka M, Inaba A (2001)** Reduction effects of CO₂ emission from steel products by reduction agent injection into blast furnace. *Nippon Kinzoku Gakkaishi*, **65**(7); 589-595 (Jul 2001) (In Japanese)
- Nightingale R J, Mathieson J G, Di Giorgio N, Chew S J, Rogers H, Simpson J F (2003)** Understanding the improved blast furnace operations at Port Kembla associated with the introduction of pulverised coal injection. In: *Proceedings, METEC congress 03, 3rd international conference on science and technology of ironmaking*, Düsseldorf, Germany, 16-20 Jun 2003. Düsseldorf, Germany, Stahlinstitut VDEh, pp 172-180 (2003)
- Official Journal of the European Union (2008)** Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union*; **51**(L312); 3-30 (22 Nov 2008)
- Ogaki Y, Tomioka K, Watanabe A, Arita K, Kuriyama I, Sugayoshi T (2001)** Recycling of waste plastic packaging in a blast furnace system. *NKK Technical Review*; (84); 1-7 (2001)
- Ökvist L S, Jansson B, Hahlin P (2006)** Effect of coal properties, injection rate and O₂ addition on BF conditions. In: *Proceedings, 4th international congress on the science and technology of ironmaking (ICSTI '06)*, Osaka, Japan, 26-30 Nov 2006. Tokyo, Japan, Iron and Steel Institute of Japan, pp 327-330 (2006)
- Osing D A A (1997)** A method for the pneumatic delivery of plastics-containing materials into a reaction vessel. Patent WO/1997/023654, Geneva, Switzerland, World Intellectual Property Organization (WIPO), vp (1997)
- Osório E, Gomes M L I, Vilela A C F, Kalkreuth W, Almeida M A A, Borrego A G, Alvarez D (2006)** Evaluation of petrology and reactivity of coal blends for use in pulverized coal injection (PCI). *International Journal of Coal Geology*; **68**(1/2); 14-29 (3 Jul 2006)
- Panagiotou T, Levendis Y (1994)** A study on the combustion characteristics of PVC, poly(styrene), poly(ethylene), and poly(propylene) particles under high heating rates. *Combustion and Flame*; **99**(1); 53-74 (1994)
- PlasticsEurope (2009)** *The compelling facts about plastics 2008. An analysis of European plastics production, demand and recovery for 2008*. Available from: www.plasticseurope.org Brussels, Belgium, PlasticsEurope, 24 pp (2009)
- Poultney R (2006)** Coal properties and their effects on plant operation. In: *Proceedings, 4th international congress on the science and technology of ironmaking (ICSTI '06)*, Osaka, Japan, 26-30 Nov 2006. Tokyo, Japan, Iron and Steel Institute of Japan, pp 609-612 (2006)
- Poveromo J J (2004)** Blast furnace fuel injection trends. In: *Met coke world summit 2004*, Chicago, IL, USA, 18-20 Oct 2004. Portland, ME, USA, Intertech, pp 1-19 (2004)
- Probst H H (1999)** Fuel blends for blast furnace injection. In: *JOULE III programme. Clean coal technology R & D. Advanced combustion and gasification of fuel blends. Volume II. Fuel blends and alkali diagnostics*. EUR—19285/II, Brussels, Belgium, European Commission, Clean Coal Technology R & D, pp 315-347 (1999)
- PWMI Newsletter (2009)** Plastic products, plastic waste and resource recovery (2007). *PWMI Newsletter*; (38); 1-6 (May 2009)
- Sahajwalla V, Gupta S (2005)** *PCI coal combustion behavior and residual coal char carryover in the blast furnaces of three American steel companies during pulverized coal injection (PCI) at high rates*. TRP report 0033, Washington, DC, USA, American Iron and Steel Institute, Technology Roadmap Program Office, 95 pp (Apr 2005)
- Sahajwalla V, Rogers H, England B, Mason M, Mathieson J G, Gupta S K, Saha-Chaudhury N (2004)** *Pilot scale evaluation of the co-injection of pulverised coal and non-chlorinated plastic waste*. Research report 57, Kenmore, Qld, Australia, CRC for Coal in Sustainable Development (CCSD), 82 pp (2004)
- Sarma B, Cramb A W, Fruehan R J (1996)** Reduction of FeO in smelting slags by solid carbon: experimental results. *Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing Science*; **27**(5); 717-730 (Oct 1996)
- Sato M, Asanuma M, Murai R, Ariyama T (2006)** Establishment of advanced recycling technology of waste plastics in blast furnace. In: *Proceedings, 4th international congress on the science and technology of ironmaking (ICSTI '06)*, Osaka, Japan, 26-30 Nov 2006. Tokyo, Japan, Iron and Steel Institute of Japan, pp 577- 580 (2006)
- Scott D H (1995)** *Coal pulverisers – performance and safety*.

- IEACR/79, London, UK, IEA Coal Research, 83 pp (Jun 1995)
- Sekine Y, Fukunda K, Kato K, Adachi Y, Matsuno Y (2009)** CO₂ reduction potentials by utilizing waste plastics in steel works. *International Journal of Life Cycle Assessment*; **14**(2); 122-136 (Mar 2009)
- Seo K, Fruehan R J (2000)** Reduction of FeO in slag with coal char. *ISIJ International*; **40**(1); 7-15 (2000)
- Sharma R (2004)** *Injection of semi-soft coal into a blast furnace at TATA steel*. Available at: www.allbusiness.com/primary-metal-manufacturing/iron-steel-mills-ferroalloy/263075-1.html San Francisco, CA, USA, AllBusiness, 17 pp (2004)
- Shen Y S, Guo B Y, Yu A B, Zulli P (2009)** A three-dimensional numerical study of the combustion of coal blends in blast furnace. *Fuel*; **88**(2); 255-263 (Feb 2009)
- SiCon (2008)** *Production successfully started*. Hilchenbach, Germany, SiCon GmbH, press release, 1 pp (25 Apr 2008)
- SiCon (2009)** *VW-SiCon process*. Available from: www.sicontechnology.com Hilchenbach, Germany, SiCon GmbH, 2 pp (2009)
- Sigmund H (2009)** We're not finished yet. *Metals & Mining*; (1); 42-43 (2009)
- Snowdon B (2008)** Reduction in landfill pollution & economic recovery of metals and energy by the innovative use of injection technology. Paper presented at: *Bulk08 seminar*, Blackpool, UK, 17-18 Apr 2008. 23 pp (2008)
- Soni, Sripriya R, Rao P V T, Sharma R P (2000)** LCA study for steel sector - analysis for blast furnace operations. *Tata Search*; 97-101 (2000)
- Sørnum L, Grønli M G, Hustad J E (2001)** Pyrolysis characteristics and kinetics of municipal solid wastes. *Fuel*; **80**(9); 1217-1227 (Jul 2001)
- Stainlay R, Bennett P (2001)** PCI coal - status and forecast. Paper presented at: *1st international meeting on ironmaking*, Belo Horizonte, Brazil, 24-26 Sep 2001. 11 pp (2001)
- Steiler J-M, Hess E (2006)** Present status and future issues of ironmaking in Europe. In: *Proceedings, 4th international congress on the science and technology of ironmaking (ICSTI '06)*, Osaka, Japan, 26-30 Nov 2006. Tokyo, Japan, Iron and Steel Institute of Japan, pp 10-17 (2006)
- Steiler J-M, Lehmann J, Clairay S (1998)** Physical chemistry of slag-metal-gas reactions in the blast furnace. In: *Proceedings, 2nd international congress on the science and technology of ironmaking and 57th ironmaking conference*, Toronto, ON, Canada, 22-25 Mar 1998. Warrendale, PA, USA, Iron and Steel Society, pp 1423-1434 (1998)
- Takaoka T, Asanuma M, Hiroha H, Okada T, Ariyama T, Ueno I, Wakimoto K, Hamada S, Tsujita Y (2003)** Development of a new recycling process of automobile shredder residue combined with ironmaking process. In: *Proceedings, 3rd international conference on science and technology of ironmaking: METEC 03*, Düsseldorf, Germany, 16-20 Jun 2003. Düsseldorf, Germany, Stahlinstitut VDEh, pp 166-171 (2003)
- Teasdale S L, Hayes P C (2005)** Kinetics of reduction of FeO from slag by graphite and coal chars. *ISIJ International*; **45**(5); 642-650 (2005)
- Tian F, Sun L, Gu M, Zhao Y, Zhou C Q (2008)** Numerical analysis on pulverized coal combustion in the blast furnace raceway. In: *AISTech 2008, proceedings of the iron and steel technology conference*, Pittsburgh, PA, USA, 5-8 May 2008. Warrendale, PA, USA, Association for Iron and Steel Technology (AIST), vol 1, pp 321-329 (2008)
- Toxopeus H L, Danloy G, Franssen R, Havelange O, Franssen C (2002)** *Massive injection of coal and superoxygenated blast into the blast furnace*. EUR 20298, Luxembourg, Office for Official Publications of the European Communities, 74 pp (2002)
- Trinnaman J, Clarke A (eds) (2007)** *2007 survey of energy resources*. Available from: www.worldenergy.org London, UK, World Energy Council, 600 pp (2007)
- Tukker A, de Groot H, Simons L, Wieggersma S (1999)** *Chemical recycling of plastic wastes (PVC and other resins)*. TNO-report STB-99-55 Final, Delft, Netherlands, Netherlands Organization for Applied Scientific Research (TNO), 132 pp (Dec 1999)
- Vamvuka D, Schwanekamp G, Gudenau H W (1996)** Combustion of pulverized coal with additives under conditions simulating blast furnace injection. *Fuel*; **75**(9); 1145-1150 (Jul 1996)
- Vinyl 2010 (2005)** *Vinyl 2010 progress report 2005*. Available from: www.vinyl2010.org Brussels, Belgium, Vinyl 2010, 48 pp (2005)
- voestalpine (2007)** *voestalpine starts up world's most advanced sinter offgas cleaning system*. Linz, Austria, voestalpine AG, press release, 2 pp (24 Oct 2007)
- Wakimoto K (2001)** A feedstock recycling system of waste plastics in a blast furnace at NKK. In: *60th ironmaking conference, proceedings*, Baltimore, MD, USA, 25-28 Mar 2001. Warrendale, PA, USA, Iron and Steel Society, pp 473-483 (2001)
- Walker W, Gu M, Selvarasu N, D'Alessio J, Macfadyen N, Zhou C (2008)** Simulation of natural gas and pulverized coal combustion in a blast furnace and their effects on coke consumption in the raceway. In: *AISTech 2008, proceedings of the iron and steel technology conference*, Pittsburgh, PA, USA, 5-8 May 2008. Warrendale, PA, USA, Association for Iron and Steel Technology (AIST), vol 1, pp 461-472 (2008)
- Waste and Resources Action Programme (2007)** *Blast furnace slag (BFS). A technical report on the manufacturing of blast furnace slag and material status in the UK*. Available from: www.environment-agency.gov.uk Banbury, UK, Waste and Resources Action Programme, 30 pp (Aug 2007)
- Wollny V, Dehoust G, Fritsche U R, Weinem P (2001)** Comparison of plastic packaging waste management options. Feedstock recycling versus energy recovery in Germany. *Journal of Industrial Ecology*; **5**(3); 49-63 (Jul 2001)
- Working Group on Strategies and Review (2001)** *Executive summary of the status report on the management of by-products/residues containing heavy metals and/or persistent organic pollutants*. EB.AIR/WG.5/2001/9, Geneva, Switzerland, UN Economic Commission for Europe, Convention on Long-Range Transboundary Air Pollution, 18 pp (11 Jul 2001)
- Wu Z (2005)** *Fundamentals of pulverised coal combustion*. CCC/95, London, UK, IEA Clean Coal Centre, 36 pp (Mar 2005)
- Yagi J, Nogami H, Yu A (2006)** Multi-dimensional mathematical model of blast furnace based on multi-fluid theory and its application to develop super-high efficiency operations. Paper presented at: *5th international conference on CFD in the process industries*, Melbourne, Vic, Australia, 13-15 Dec 2006. 6 pp (2006)

- Zevenhoven R, Karlsson M, Hupa M, Frankenhaeuser M (1997)** Combustion and gasification properties of plastic particles. *Journal of the Air and Waste Management Association*; **47**(8); 861-870 (Aug 1997)
- Zhang S, Bi X (2003)** Theoretical consideration of problems relating to high coal rate injection into blast furnaces. *Ironmaking and Steelmaking*; **30**(6); 467-474 (Dec 2003)
- Zhou L, Luo T, Huang Q (2009)** Co-pyrolysis characteristics and kinetics of coal and plastic blends. *Energy Conversion and Management*; **50**(3); 705-710 (Mar 2009)
- Zhu R, Guo K (2000)** Characteristic of 200 kg/thm PCI and low coke rate of BF in Baosteel. In: *59th ironmaking conference proceedings*, Pittsburgh, PA, USA, 26-29 Mar 2000. Warrendale, PA, USA, Iron and Steel Society, pp 321-326 (2000)
- Ziębik A, Stanek W (2001)** Forecasting of the energy effects of injecting plastic wastes into the blast furnace in comparison with other auxiliary fuels. *Energy (Oxford)*; **26**(12); 1159-1173 (Dec 2001)