PCI COAL – STATUS AND FORECAST

[1] Ross Stainlay
[2] Philip Bennett

Over the last two decades pulverized coal injection has been a process refinement to the blast furnace route for the production of crude steel that has assisted the steel industry to lower operating costs, extend coke oven life and lower greenhouse emissions. Pulverized coal injection technology for the milling, storage, distribution to tuyeres and injection into the furnace has matured, with most problems associated with blockages in bins, transport lines and tuyeres now overcome. As the understanding of the impact of quality of the injected coal has increased, there has been a shift from high volatile thermal coals to low volatile semi-anthracites. The move to low volatile coals was primarily driven by the increased savings associated with higher coke replacement rates, and the ease of milling of the softer coals. With injection rates of over 200 kg/t hot metal the injected coal becomes a major source of not only energy but ash and other impurities. Blending of injected coals offers advantages in controlling slag chemistry and improving gasification of the coal within the tuyere and raceway, whilst maintaining a high replacement ratio. Seaborne PCI coal trade is estimated at 31 million tonnes in 2000 and is projected to rise to 37 million tonnes in the year 2005. Queensland low volatile coals account for about one third of this market.

Keywords: PCI, trade, forecast

1st International Meeting on Ironmaking, September 24th to 26th, 2001 – Belo Horizonte - Brasil

[1] General Manager, Marketing – Jellinbah Resources Pty Ltd <www.jellinbah.com.au>
[2] Principal Consultant – CoalTech Pty Ltd <www.coaltech.com.au>

Introduction

Blast furnace technology is central to the crude steel industry and is continually undergoing refinements to improve productivity and reduce operating costs. In the next two decades the blast furnace route for iron production will continue to contribute 50 to 60 % of world requirements. It will be the preferred route wherever the demand is large, scrap is not available, iron ore and coal are available and electric power is expensive (EUROFER, 1999). Continuous improvements in productivity, coke consumption and fuel use within the steelworks have been driven by competition in world steel markets. Prior to the 1980's the preferred injection fuel was oil, but sharply increasing oil prices led to other fuels being used, such as natural gas in USA and Australia and coal in most other countries.

Hot metal production is the most energy intensive stage of the steel making process, and this energy consumption can be linked to operating costs and greenhouse emissions. For this reason, efforts have been focused primarily on process refinements at the blast furnace where fuel consumption of the blast furnace has been lowered. For example in Germany the fuel rate has decreased from 795 kg per tonne hot metal (kg/tHM) in 1960 to a current consumption of 501 kg/tHM (ECOAL, 2000).

Pulverized Coal Injection (PCI) is one such process refinement that has been implemented in most steelworks around the world. Increased injection of coal was initially driven by high oil prices but now increased use of PCI is driven by the need to reduce raw material costs and also by the need to extend the life of ageing coke ovens.

The injection of coal into the blast furnace has been shown to:

- Increase the productivity of the blast furnace, i.e. the amount of hot metal produced per day by the blast furnace;
- Reduce the consumption of the more expensive coking coals by replacing coke with cheaper soft coking or thermal coals;
- Assist in maintaining furnace stability; and
- Improve the consistency of the quality of the hot metal and reduce the silicon content of the pig iron.

Figure 1 shows how the coke rate varies with pulverized coal injection rates. The large scatter in this plot is due to the data being taken from the monthly average figures from a range of blast furnaces in various countries injecting a wide range of coals. The data indicates that there appears to be a reduction in incremental replacement ratio at high injection rates.

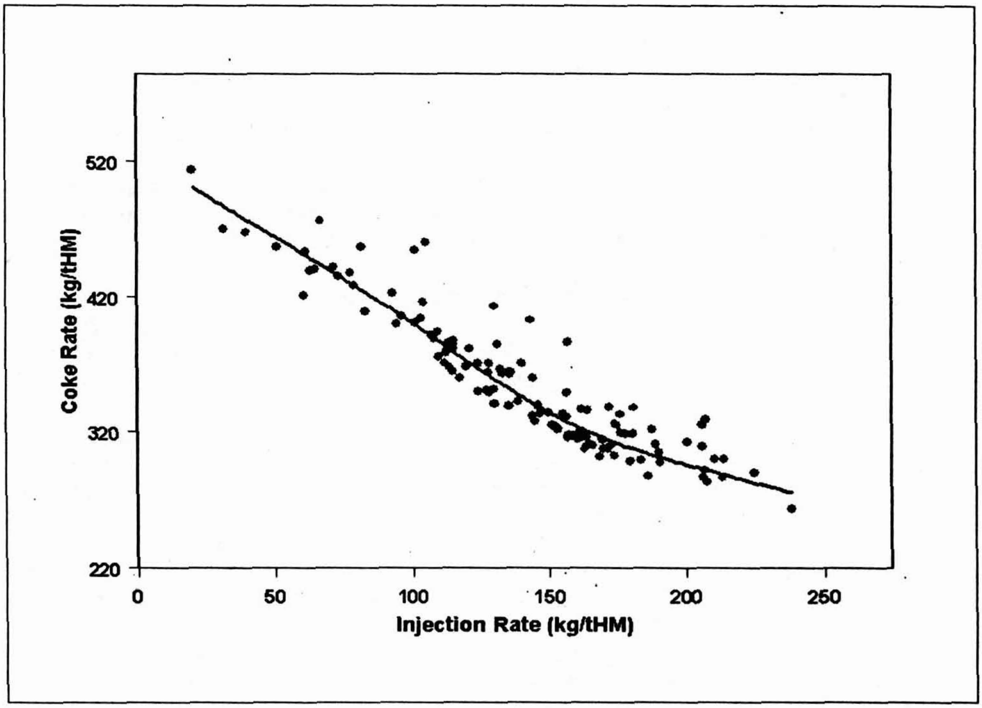

Figure 1 – Coke rate versus coal injection rate

Coal Selection

There are many criteria used to measure the performance of coal injection, both technical and economic, such as the following:

- The coke replacement ratio (kilograms of coke replaced per kilogram of coal injected). A "corrected" replacement ratio is sometimes calculated, taking account of other changes in the energy and mass balance besides the reduced coke rate.
- Mills in some injection systems are being operated at rates close to or greater than the design rate. The use of softer coals in these mills will increase injection capacity.
- In some PCI systems, concern over potential blockages within pulverized coal transfer lines or bins may limit selection of coals.
- Coal properties may impact upon operating and or downstream processing costs. These costs are heavily dependent on the other raw materials and the design of particular steelworks.

Coal quality may impact on many aspects of performance:

- *Milling.* Hardgrove Grindability Index (HGI) can provide a reasonable prediction of mill power requirements, but the operator may have to use trial and error to obtain the required coal fineness. Coals with a low Abrasion Index can usually be relied upon to produce low levels of mill wear.

- *Handling.* Coarse coal handling capability is primarily determined by moisture and fines content. Difficulties in pneumatic handling of milled coal primarily depends on the size distribution of the product, which is influenced by HGI.

- *Combustibility.* Fast burnout is associated with high volatile coals.

- *Char interaction with coke.* The entry of unburnt coal char into the burden is inevitable at high injection rates.

- *Blast preheat and oxygen enrichment requirements.* The cooling effect that coal injection has on the raceway flame temperature can be compensated by increased blast temperature and/or oxygen enrichment. The cooling effect is greater for high volatile coals.

The relative importance of different aspects of coal quality has varied, as the technology for injection has improved and the rate of injection increased. In the late 1970's, triggered by the oil crisis, interest in PCI was renewed and coal was considered as an economic replacement fuel for oil. In the early 1980's PCI rates in Europe and Japan were below 40 kg/tHM and research focussed on improved combustion of coal in the raceway. Much of this research highlighted that the combustibility of the char depended on the volatile matter of the coal (McCarthy et al, 1986) and many of the coals used for injection during this period were high volatile thermal coals.

In the early 1990's, injection rates increased to over 100 kg/tHM. Notable high injection rates at this time were:

- 194 kg/tHM at Sollac's Dunkerque No. 4 blast furnace during May 1992 (Lao et al, 1994);

- 200 kg/tHM at Ilva's Taranto works (ICR Fax, 1994); and

- 212 kg/tHM at Hoogovens' No. 6 blast furnace at IJmuiden during December 1992 (Koen et al, 1993).

At these higher injection rates it was observed that changes were occurring in the operation of the blast furnace. Some of these changes included:

- The size of the raceway;

- Reduction of permeability of the coke surrounding the raceway (Figure 2);

- Changes in temperature distribution in the raceway; and

- Mechanical degradation of coke in the raceway.

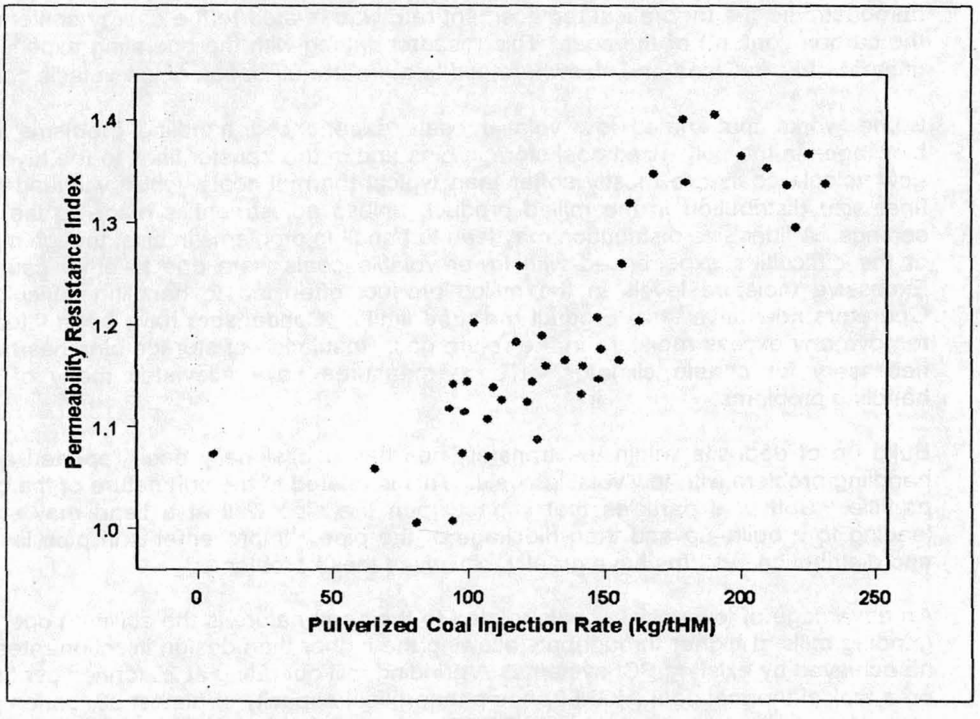

Figure 2 - Influence of injection rate on lower coke burden permeability resistance index (Maki et al, 1996)

All of these observed changes influence raceway stability and the distribution of gas flow through the lower sections of the blast furnace, both of which impact upon furnace stability and productivity. Unburnt char entering the raceway and the changes in the distribution of coke were thought to be the major causes for these changes. Therefore most steelworks with high injection rates continued to use high volatile coals or blends containing mostly high volatile coals to reduce the level of unburnt char.

With revised burden distribution and the use of stronger coke many of the problems relating to gas flows at high injection rates were overcome. These improvements in blast furnace operation together with the understanding that much of the carbon carry-over with coal injection was not char from the coal but was fine coke and soot reduced the emphasis on complete combustion. Also, though lower volatile coals produce more char, the reactivity of char from all coals is about an order of magnitude higher than coke leading to the preferential consumption of all char regardless of the coal injected.

PCI was no longer considered as the replacement for oil but a means of replacing coke and research was then focussed on the issues relating to coke replacement rate. Higher potential cost savings result from higher replacement ratios. Early modelling work conducted, for example at CANMET (Hutny et al, 1990), demonstrated the theoretical replacement rate was related to the energy content (or the carbon content) of the coal. This research, along with the operating experience of steelworks in China and elsewhere, led to a greater utilisation of low volatile coals.

Some works that trialed low volatile coals experienced handling problems with blockages in the pulverized coal storage bins and in the transfer lines to the tuyeres. Low volatile coals are mostly softer than typical thermal coals, which will lead to a finer size distribution in the milled product, unless adjustment is made to the mill settings. A finer size distribution may lead to handling problems in bins, though many of the difficulties experienced with lower volatile coals were due to other causes. Excessive moisture levels in the milled product often led to handling difficulties. Operators now have strict product moisture limits. Condensers have been fitted to remove any excess moisture in the return gas. Insulation of storage bins has been necessary for certain climates. These measures have alleviated many of the handling problems.

Build up of deposits within the transfer lines has occasionally been reported as a handling problem with low volatile coals. This is related to the soft nature of the coal particle. Soft coal particles that impact upon the pipe wall at a bend may stick, leading to a build–up and then blockage of the pipe. Improvements in pipe layout and distribution systems have greatly minimised these problems.

An advantage of low volatile coals related to their soft nature is the ability to operate grinding mills at higher throughputs allowing the higher than design injection rates to be achieved by existing PCI systems. A grinding mill operating at 20 tonnes per hour on a typical thermal coal (HGI 50) has a theoretical capacity of almost 30 tonnes per hour when milling a softer coal (HGI 80–85).

With solutions to the handling problems, good replacement ratios and the ability to operate PCI systems at higher throughput, the use of low volatile coals for injection increased rapidly from the mid 1990's.

At moderate to high injection rates (140 to 170 kg/tHM) the current status of the technology for coal injection allows for a wide range of coals to be utilised. Choosing a high energy, low volatile coal gives the maximum possible replacement ratio. The ultimate level of injection within any steelworks is dependent on many factors related to the particular works.

At high levels of injection (say over 180 kg/tHM) issues relating to the gas flow through the coke bed and the role the injected coal plays in the reduction of the ore become increasingly significant. At ultra-high injection rates it has been estimated (Lüngen and Poos, 1996) that for an injection rate of 250 kg/tHM (coke rate of around 250 kg/tHM) the amount of coke gasified at the tuyeres can be as low as 20 % of the total coke. The remaining coke is gasified or dissolved by reactions occurring in the shaft and the bosh areas, i.e. before the coke reaches the tuyeres. The residence time of the coke, at high PCI rates, is 3 to 5 times that of an all coke operation, leading to a size reduction of 40% of the original charged coke. The increased residence time of the coke impacts on the coke's ability to cope with the harsh environment in the raceway. This, together with the decrease in coke size due to greater consumption, will increase the amount of coke fines and therefore decrease coke bed permeability.

However, as noted by Toxopeus et al (2001) the increase in the pressure drop with increased injection rates occurs in the upper levels of the furnace. This indicates that the major cause of decreasing bed permeability is the decreasing coke/ore ratio in the burden.

In modelling coal combustion in a blast furnace Ohno et al (1994) used actual data to estimate the amount of injected coal that is consumed by in-furnace reactions, i.e. solution loss. Based on this model it was predicted that injection rates of 300 kg/tHM could only be achieved with perfect mixing of coal and oxygen and an oxygen concentration of 65 %. Modelling carried out by Maki et al (1996) indicated that the maximum injection rate would be 190 kg/tHM for a single lance, 210 kg/tHM for a double lance and 230 kg/tHM for an eccentric double lance. The increase in injection rates for the different lance designs was attributed to better mixing of coal and oxygen, reducing the amount of unburned char that is required to be consumed by the solution-loss reaction.

This modelling work and operating experiences indicate that complete gasification of the char is beneficial at high injection rates. Increasing the intensity of combustion by increasing oxygen, increasing temperature or improving mixing within the tuyere improves combustion, as shown by the early work of Suzuki et al (1984). Increasing the intensity of combustion not only increases the reaction rates but also greatly enhances the volatile matter yield (Bennett, 1997). Fragmentation of the char is also increased reducing the char diameter and therefore significantly speeding the diffusion limited kinetics (Liu et al, 2000).

Improvements in lance designs, including oxy-coal lances, have greatly increased the intensity of combustion with advanced designs achieving near total gasification of the coal within the tuyere (Langner, 1998).

There is also evidence that increased hydrogen content of the fuel can also be beneficial. For example, improvements in coke rate and furnace permeability were noted with co-injection of natural gas at Bethlehem Steel's Burns Harbor blast furnaces (Hill et al, 2001). In this study the natural gas was injected in separate tuyeres from those used for granulated coal injection. Agarwal et al (1992), in comparing the economics of injecting natural gas, oil and coal into blast furnaces in North America, examined the effects of hydrogen on blast furnace performance. The hydrogen is derived from two sources: the dissociation of blast moisture and the injected fuel. The hydrogen impacts on blast furnace operation by a variety of physical, thermochemical and kinetic effects. These effects are:

- *Physical Effects.* An increase in the percentage of hydrogen in the bosh gas will decrease the density of the bosh gas and therefore will reduce the pressure drop or allow a greater gas flow for the same pressure drop.

- *Thermochemical Effects.* As injection rates increase to high levels a significant amount of the fuel is consumed in the reduction of FeO. As the reduction by hydrogen is less endothermic than the C-FeO solution loss reaction, there is a decrease in energy requirements in the reduction zone.

- *Kinetic Effects.* The diffusivities of H_2 and H_2O are significantly higher than those of CO and CO_2. Higher diffusivities will increase the reduction rate, particularly at lower temperatures.

The blending of the coals to be injected enables better control of coal quality and allows the selection of a blend with suitable carbon for good replacement ratio and volatile content for combustion. The combustion performance of a coal blend is more complex than that of a single coal because it is not only dependent on the combustion performance of the component coals but also on the interaction between these coals. This interaction between coals first occurs in the milling of the blend where there is potential for large differences in the size distribution of the component coals, especially if there are significant differences in the hardness of each coal (Bennett, 2001). This interaction between component coals of a blend can enhance the combustibility of a blend while achieving a high replacement ratio (Carneiro, 2001).

The importance of blending will increase as injection rates approach the theoretical maximum and will provide furnace operators the flexibility in coal selection to meet their particular needs. This flexibility will not necessarily be achieved by injecting single coals.

Coal Trade

According to ABARE (Maurer et al, 2001) the world metallurgical coal trade will increase moderately with the expected negative growth in the Japanese market to be offset with growth in demand from Chinese Taipei, Republic of Korea and Brazil. World blast furnace production is projected to rise by an average 1.2 % a year over the five years to 2006, after having risen at an average annual rate of 2.6 % in the previous five years. The growth of metallurgical coal trade should be greater than the expected increase in iron production as there will be a greater growth in production in countries that import coal.

As PCI technology matures there has been a rapid growth of world seaborne coal trade as shown in Figure 3. The first major growth period (late 1980's to mid 1990's) corresponded to the adoption of PCI technology by most steelworks. A second major growth period started in the late 1990's and was due to coal injection rates increasing to an average of around 130 kg/tHM. The current level of seaborne PCI coal trade is approximately 31 million tonnes per annum and is forecasted to grow to 40 million tonnes by 2010 (Jonker, 2001). This tonnage will be achieved if the average injection rate increases from the current level to around 180 kg/tHM with no growth in blast furnace production. Alternatively a predicted 1.2 % increase per annum in blast furnace iron production coupled with an increase in average PCI rates to 160 kg/tHM will yield the same PCI coal trade in the year 2010.

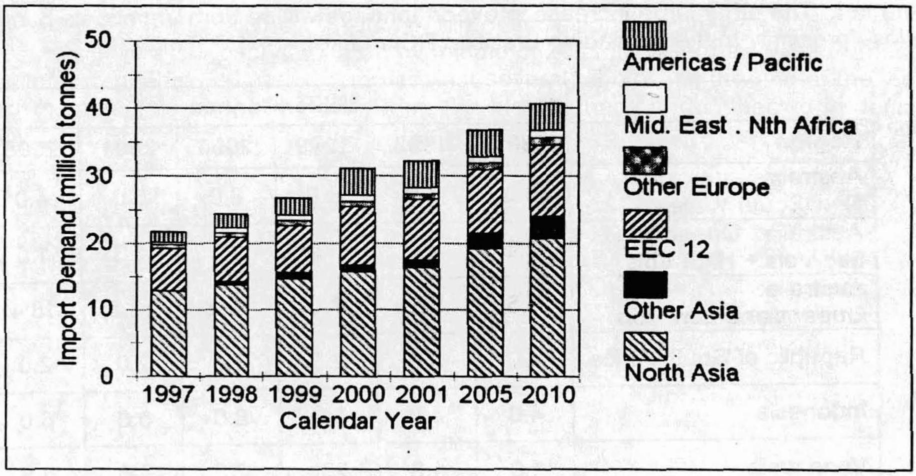

Figure 3 – PCI seaborne coal trade by destination (Jonker, 2001)

As shown in Figure 4 the growth in the PCI coal trade has been reflected in a strong increase in the exports of low volatile coals from Queensland Australia. Queensland low volatile coals currently account for one third of the seaborne traded PCI coals.

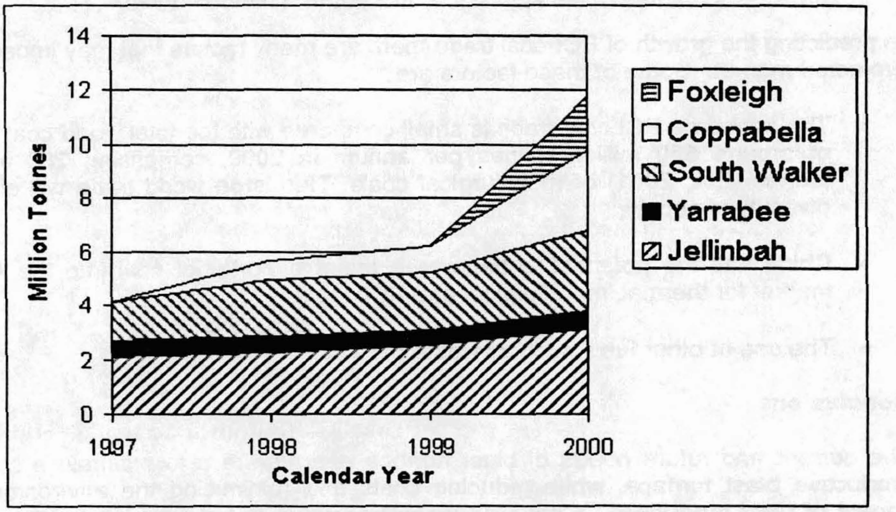

Figure 4 – Queensland low volatile coal exports

This preference for low volatile coals for injection and the increased overall demand for PCI coals has lead some market analysts to predict a significant growth in the export of semi-anthracites from Queensland as shown in Figure 4. Some of this growth in Queensland's low volatile coal exports will offset the decline in exports from New South Wales as these coals move back into their traditional thermal coal market. The other large increase in export tonnage will be from Venezuela due to its close proximity to the expanding Brazilian PCI market.

	Million tonnes					
Region	**1997**	**1998**	**1999**	**2000**	**2001**	**2005**
Australia: New South Wales	6.0	6.0	6.0	6.0	5.0	4.0
Australia: Queensland Mid Vols + High Vols	2.0	2.0	2.0	2.0	1.3	1.0
Australia: Queensland Low Vols	3.5	5.2	7.0	10.8	13.5	18.4
Republic of South Africa	4.0	3.0	2.5	2.0	2.0	2.0
Indonesia	4.0	4.0	5.0	6.0	6.0	6.0
Venezuela	1.0	1.8	2.1	2.5	2.6	3.3
Other	1.2	2.3	2.1	1.8	1.7	2.0
PCI COAL TOTAL	**21.6**	**24.3**	**26.7**	**31.1**	**32.1**	**36.7**

Table 1 – Supply of seaborne PCI coal (Jonker, 2001)

In predicting the growth of PCI coal trade there are many factors that may impact the projected market. Some of these factors are:

- The seaborne PCI coal trade is small compared with the total world coal trade of around 550 million tonnes per annum in 2000, comprising 200 million tonnes (EIA, 2001) of metallurgical coals. This large world trade will ensure diversity of supply;
- China has the potential to become a major exporter of coal into the Asian market for thermal, metallurgical and PCI coals; and
- The use of other fuels such as waste plastics.

Conclusions

The current and future needs of blast furnace operators are to maintain a stable, productive blast furnace, while reducing costs and minimising the environmental impact of steel production. Coal injection will continue to be a means for the steel industry to address these needs with low volatile coals being the preferred coals. Blending of injected coals offers advantages in controlling slag chemistry and promoting the gasification of the coal within the tuyere and raceway while maintaining high replacement ratios. Seaborne PCI coal trade is estimated at 31 million tonnes in 2000 and is projected to rise to 37 million tonnes in the year 2005. Queensland low volatile coals account for about one third of this market.

References

Agarwal, J.C., Brown, F.C., Chin, D.L., Frydenlund, A.R., 1992, "A model for economic comparison of natural gas, oil, and coal injection in the blast furnace", *Topical Report - Gas Research Institute*, No. 5089-235-1772, Sept., 1992.

Bennett, P.A., 1997, Coal characterisation for PCI, *ACARP End-of-Grant Report C7001*, December 1997.

Bennett, P.A., 2001, Combustion of coal blends, *The Pittsburgh Coal Conference*, Newcastle, Australia, December 2001.

Carneiro, R.T.S., Sad, H., Júnior, H.R.S., 2001, Coal selection methodology for blast furnace injection, *2001 Ironmaking Conference Proceeding*. Iron & Steel Society, March 2001, Baltimore Maryland USA.

Ecoal, 2000, World Coal Institute, Volume 35 September 2000.

EIA 2001, *International Energy Outlook 2001*.

EUROFER 1999, Technology Road Map to Determine the Research Priorities of the European Steel Industry January 1999.

Hill, D.G., Dwelly, M.J., Strayer, T.J., 2001, "Why low volatile granular coal is the choice for coal injection at Bethlehem Steel's Burns Harbor blast furnaces", *2001 Ironmaking Conference Proceeding*. Iron & Steel Society, March 2001, Baltimore Maryland USA.

Hutny, W.P., Price, J.T., Gransden, J.F., 1990, Evaluation of coals for blast furnace injection using a computer model, *Ironmaking Conference Proceedings*, 1990.

Jonker, C., 2001, private communication, *Barlow Jonker Pty Ltd.*

Langner, K., 1998, Integrated injection of pulverized coal IIPC – a new technology for advanced iron-making processes, *The Changing World of Coal in the Steel Industry*, London, June 1998.

Liu, G., Wu, H., Gupta, R.P., Lucas, J.A., Tate, A.G., Wall, T.F., 2000, Modelling the fragmentation of non-uniform porous char particles during pulverized coal combustion, *Fuel*, 79, pp627–633.

Lüngen, H.B., and Poos, A., 1996, Injection of coal into the blast furnace - ECSC synthesis report. *Cokemaking International*, Vol. 8, No. 2, 1996.

Maki, A., Sakai, A., Takagaki, N., Mori, K., Ariyama, T., Sato, M., Murai, R., 1996, "High rate coal injection of 218 kg/t at Fukuyama No. 4 Blast Furnace", *ISIJ International*, Vol 36, No 6, pp 650-657.

McCarthy, M.J., et al., 1986, "Replacement of oil by coal injection", *NERDD End of Grant Report No 602, Dept. of Primary Industry and energy, Australia*, 1986.

Maurer, A., Donaldson, K., Schneider, K., 2001, "Coal outlook to 2005-06" *ABARE Conference Outlook 2001*.

Ohno, Y., Furukawa, T., Matsu-Ura, M., 1995, Combustion behavior of pulverized coal in a raceway cavity of blast furnace and its application to a large amount injection. *ISIJ International*, Vol. 34, No. 8, 1995.

Suzuki, T., Hirose, T., Morimoto, K., Abe, T., 1984. High intensity combustion of coal for Application To A Blast Furnace, *Twentieth Symposium (International) On Combustion, University Of Michigan, Michigan*, August 1984.

Toxopeus, H.L., Steeghs, A.G.S., van den Boer, J.F.C., 2001, PCI at the start of the 21st century, *2001 Ironmaking Conference Proceeding*. Iron & Steel Society, March 2001, Baltimore Maryland USA.