A Review of Recent Research in Australia on Ironmaking*

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I. Introduction

The history of ironmaking in the blast furnace had similar beginnings in both Japan and Australia as primitive masonry furnaces started operation in both countries at about the same time (Kamaishi 1858 and Mittagong 1864).

Even in those early days, there was interest in direct processes for making steel which would avoid the necessity for the blast furnace. In 1869, William Siemens produced steel by reducing crushed ore with solid fuel in a rotating cylindrical furnace and discharging the resultant sponge iron into a steel melting furnace. After several years of experimentation, Siemens was convinced that the process would make better, cheaper steel, and he built a commercial plant in 1877. This was abandoned after two years because of high production costs, and at that time the great British ironmaster, Lowthian Bell, wrote to Siemens "I have a kind of instinctive feeling that the blast furnace will be difficult to eliminate ".

This "instinctive feeling" remains with most of us today, and the blast furnace is likely to be the major commercial method of reducing iron ore at least until the year 2000.

Since the blowing-in of its first blast furnace in 1858, Japan has developed the most advanced blast furnace technology in the world, and last year (1982) produced 77.5 Mt of blast furnace iron in comparison with a production of 6.0 Mt in Australia. This difference in scale between the ironmaking industries of both countries is also reflected in the coke utilization (45.3, 4.3 Mt) and sinter production (93.0, 5.5 Mt). A similar difference in the scale of research on these products must also be anticipated, and Australia has had to be very selective in the concentration of research activity in order to make maximum use of the smaller funds available for research. This paper outlines the relevant research which has been done since the conclusion of World War II.

Before commencing the review it is necessary to note that the three ironmaking centres in Australia each have quite different ironmaking practices because of the differing raw materials:
Newcastle —uses local low rank coal and imports all iron ore, mainly from Mt. Newman; furnace burdening is mainly fluxed sinter;
Port Kembla —uses local medium rank coal with high inerts and imports all iron ore, mainly from Mt. Newman;
Whyalla —imports all coal of variable mix and uses local iron ore, mainly as fluxed pellets.

Because of the raw materials situation, Australian blast furnace practices are very different from those used in Japan, and our research has had to concentrate on different problems. In spite of the differences in burdening, in recent years we have gained greatly from the Japanese experience, and have a particular debt to the assistance provided by the Nippon Steel Corporation.

Research related to blast furnace operation and its raw materials in Australia is mainly performed in Universities, Government Laboratories (Commonwealth Scientific and Industrial Research Organisation, i.e., CSIRO), Industry Laboratories (Amdel and Australian Coal Industry Research Laboratories Ltd., i.e. ACIRL) and the various laboratories of The Broken Hill Proprietary Co., Ltd. (BHP). This research is encouraged by the AusIMM through its sponsorship of conferences, as exemplified by four successful international symposia held under AusIMM auspices over the last decade, as follows:
Blast Furnace Injection, Wollongong, 1972
Blast Furnace Aerodynamics, Wollongong, 1975
Utilisation of Steelplant Slags, Wollongong, 1979
Blast Furnace Hearth and Raceway, Newcastle, 1981.

The overall level of this research intensified about 10 years ago in response to the need for better information on blast furnace operation and to provide technical support for exports of iron ore and coking coal. Some of this work is reported in the other Australian papers being presented at this Joint Symposium, and this paper reviews the general trends of this research in Australia.

II. Coking Coals, Cokemaking and Coke Properties

1. Early Developments

Australian research on coking coals and the cokemaking process did not begin on any significant scale until the late 1950's.

During the 1950's, CSIRO and began a survey of the properties of various (then known) Australian coals, some carbonisation test work was being done on a small scale, and significant fundamental research

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had been commenced. An important contribution by CSIRO was the early research on mesophase formation\textsuperscript{11} and on the behaviour of inertinites during pyrolysis.\textsuperscript{21}

Subsequently, the contribution of CSIRO in these areas has diminished as non-Government laboratories opened and gradually increased their efforts in this and related research fields.

In 1957, the BHP Central Research Laboratories (CRL) were opened and coal and coke research has been a significant part of that laboratory's programmes since that time.

At about the same time, the Works Research Laboratories of BHP's major centres, Port Kembla and Newcastle, also commenced cokemaking investigations, mainly through the use of pilot scale coke ovens to test various coal blends for use in their respective plants.

The activities of ACIRL are linked with the development of the Australian coal industry's export coking coal trade, and began in the early 1960's.

2. Coal Characterisation

At CRL, the initial work concentrated on fully characterising the coking coals which were then being used by or were available to BHP. Special attention was given to the mineral matter of these coals, especially as they generally had high mineral contents even after washing. This led to semi-quantitative identification of various minerals and also to a method of separating them from coal by oxidation at low temperature.\textsuperscript{31} Further development culminated in a method of determination of mineral matter and water of hydration of minerals using radio-frequency ashing\textsuperscript{41} which has now been adopted as an Australian Standard Method.\textsuperscript{50} Knowledge of mineral matter content permitted conversion of coal analyses to a dry, mineral matter free basis and allowed scientific classification and valid comparison with foreign coals. Petrographic studies of coals were also commenced and have been continued to the present time.

Research on the carbonisation process was also commenced around 1960. Standard tests such as the crucible swelling number test, Gray King coke type determination, Audibert–Arnu dilatometer test and Gieseler plastometer test were commissioned and these four have been used as routine tests to the present time.

Other laboratory-scale work on carbonisation or pyrolysis has included Gray King assay, penetration (Sapoznikov) plastometer,\textsuperscript{60} Koppers expansion test, high temperature dilatometry, thermogravimetric studies,\textsuperscript{7} and differential thermal analysis (mainly of minerals separated from coals).

Somewhat larger scale carbonisation investigations were done using one-pound (0.45 kg) ovens\textsuperscript{7} to study the development of strength and the behaviour of each of the organic elements during carbonisation.

Some of the coals used by BHP can be affected by oxidation during stock-piling and much effort during these early years was directed, by CRL and Works laboratories, to reducing these effects by improving stockpiling techniques, and to studying the nature of oxidation and its effects on cokemaking.\textsuperscript{9} This is no longer a serious problem provided suitable precautions are taken by plant management. ACIRL has also extensively studied the oxidation characteristics of Australian coals.

Fundamental coal and coke research has also been undertaken at CRL since 1960. This has included studies on the organic constitution of coal,\textsuperscript{100} the physical (porous) structure of coals and their relation to other properties, and coal–mineral associations.

Work on coal chemical analysis has led to the direct determination of mineral matter and its water of hydration and direct oxygen determination.\textsuperscript{4,111} The percentages of mineral matter and the five major organic elements must sum to 100±0.3 before an analysis is accepted.

A constant subject of research has been the prediction of coke physical quality from coal properties. Our conclusion after many years of work by CRL and ACIRL is that a universal, accurate prediction of coke strength from say two or three coal blend properties is not feasible.\textsuperscript{112} However in certain circumstances, it is possible to predict changes to coke strength resulting from an alteration to a blend.\textsuperscript{110}

These studies required coal petrographic work which has been undertaken by CSIRO, BHP laboratories, ACIRL and other Australian organisations such as universities. All these centres have participated in activities of the International Committee on Coal Petrology (ICCP). Both CRL and ACIRL use "Quantimet" image analysers for development of automatic characterisation of both coal and coke. Important contributions have been made to the question of "reactive inertinites" in Australian coals.\textsuperscript{114}

Very encouraging results have been obtained from the application of Fourier Transform Infrared (FTIR) spectroscopy to the study of coals. The FTIR spectra between 2 100 and 300 wavenumbers from 43 bituminous coals have been analysed by factor analysis, and factor loadings have been related to measured coal properties by multiple linear regression methods. Correlation coefficients of 0.97 and above have been obtained for many chemical and physical properties. Fugre 1 gives an example of the correlation between calculated and actual Volatile Matter. This work is being extended to the characterisation of coal blends and to the prediction of certain coking properties from FTIR analysis of the component coals.

CRL has also been responsible for coal evaluation associated with BHP's exploration activities. This has taken up a large part of the laboratory's effort in coal and cokemaking and has produced a vast quantity of data, mainly from bore cores. Decisions on coal resource developments have been based largely on these results. Evaluation of new coal areas has involved test coke oven work using blends containing foreign coals as well as Australian components.

Similar survey work has been undertaken by
ACIRL on a wider range of Australian coals, also in some cases, using samples of overseas coals.

3. The Cokemaking Process

In the 1950s, the need for test coke ovens was recognised for the evaluation of coals and blends and for studies on the effects of variations in cokemaking conditions. Even today, despite the very significant growth in our knowledge of the process, test ovens are still essential for cokemaking evaluations.

A 500 kg test oven was built at Newcastle Works Research Laboratories in 1956 and has since been used to coke approximately 4,500 charges, mainly of blends for use of potential use in the Newcastle batteries. An excellent correlation has been developed with the Newcastle batteries which permits reliable prediction of coke strength and size analysis, both at the coke wharf and after transport to the blast furnaces.

At the Port Kembla Works, similar work was commenced using pilot ovens. In 1965, an electric movable wall oven was installed as it was suspected that one of the coals (Wongawilli Seam) used in the Port Kembla blend could develop excessive pressures if used in proportions greater than 40–50%. These fears were subsequently shown to be unfounded. Later, a 25 kg test oven was designed and built and has been used successfully for scouting investigations relevant to this plant.

At CRL, fifteen-pound (7 kg) electric ovens were also used for coking studies, this being the smallest size oven capable of producing sufficient coke for a reduced-scale tumbler test. ACIRL also began test oven work with 7 kg ovens, mainly to determine carbonising properties of bore core samples generated in coking coal exploration programmes. At a later stage (1975), a large capacity movable wall test oven was installed to produce coke under conditions which more closely simulated industrial slot oven practice, to determine wall pressure during coking and to produce sufficient coke for determination of "cold" strengths using internationally accepted drum tests.

In 1967, a 100 kg test oven was built at CRL and has operated ever since, having now coked about 1,400 charges. In designing this oven, two important requirements were stipulated. First, the charge bulk density should be the same as in a battery oven. This required charging in a pre-packed cardboard box rather than the more usual gravity charging method. Second, the design was required to maximise heat transfer from the sides of the charge (simulating a battery oven) and minimise heating from the top, bottom and ends. Special features were incorporated to promote this condition. As a result, this oven can produce coke with the same strength as plant coke for a full range of blend types and without the necessity for corrections to strength indices.

When only small amounts of coal are available (e.g., bore core samples) the charging box may be subdivided into compartments so that charges as small as 10 kg may be coked. This technique has been found preferable to the use of 7 kg ovens.

The suitability of several "new technologies" for cokemaking in Australia have been tested at CRL, BHP Works laboratories and ACIRL. Charge preheating facilities were provided for the Newcastle Works 500 kg oven and the effects of this process were investigated for a range of BHP blends. Briquetting equipment was installed at CRL and the use of briquettes in the charge has been studied mainly at that laboratory. Stamp charging and dry quenching have also been investigated by test oven work. The effects of selective grinding of BHP coals have been well known since the early sixties and have been investigated by all the BHP laboratories and ACIRL.

Of the above processes, some of which are in use in Japan, only the latter seems likely to be economically viable in the Australian industry in the foreseeable future.

The possible use of additives to coking blends has also been investigated over a number of years. Additives tested have included char, bentonite, iron...
ores and coke breeze (mainly as additions to the high volatile Newcastle coals), tar, pitch, solvent refined coal, and heat-affected coals. None of these has been technically or economically suitable for plant use although all BHP batteries use oil additions for bulk density control. A considerable research effort was required to reach an optimum combination of fine grinding and bulk density control at all the Works centres.

Prior to about 1964, coke for the Newcastle blast furnaces was made from the high volatile, high fluidity local coals. Coke quality was very poor, being high in ash (greater than 16%) and low in strength (less than 25 ASTM stability factor). Improvement could have been obtained by the use of non-coal additives, blending studies showed that the addition of about 12.5% of Metropolitan coal (high rank, high inerts Bulli Seam from Metropolitan Colliery in the Port Kembla coal area) provided a large improvement in coke strength. This component has been used in the Newcastle blend since that time and coke strength has been satisfactory for the relatively small furnaces in use.

In recent years, accurate economic evaluations of coking coals have become possible owing to improved knowledge of the effects of coal blend changes on coke quality and the effects of coke quality on blast furnace performance. At CRL, computer models are being developed to calculate the relative values of coking coals on a specified plant and as components of a specified blend type. Such methods are extremely useful in evaluating coals for BHP’s use and for export.

From about 1960, continuous coking processes were a major part of CRL cokemaking research and this led to the development of a new formcokemaking process, “Auscoke”. In 1970–1971, a 100 t/day pilot plant was built at Port Kembla and by 1975, the product had been successfully tested in limited blast furnace trials. Unfortunately, due to the economic downturn in the industry in 1975, the pilot plant was closed down, and further development was curtailed. “Auscoke” is still considered possibly viable for the future, should technological requirements and economic conditions again become favourable.

Heat transfer into a coal mass during coking has also been investigated. This research was particularly important in the “Auscoke” process in which heating rates have a major influence on product quality.

4. Coke Properties

In current research at CRL, more attention is being given to the behaviour of coke in the blast furnace since it has been recognised that cold tumbler tests and size measurement are not sufficient for proper coke assessment.

The observations on samples extracted from Japanese quenched blast furnaces a few years ago provided extremely useful information on the degradation of coke in various zones. This has been supported by studies of coke samples extracted through the tuyeres from all Australian furnaces and several overseas furnaces. Examination of such samples provides information on the physical and chemical mechanisms which determine the performance of coke in the furnace.

One objective of current CRL work is to study coke reactions in the laboratory to determine what processes lead to the structures and textures seen in tuyere cokes. This work includes the study of coke reactions with carbon dioxide and other gases and the effects of reactions between the ash constituents and coke carbon. The effects of alkanols on this behaviour are also being studied. Some aspects of this work are covered by two papers to this conference.

Microtextural analysis of coke is a technique which is proving invaluable in this work. However, contacts with other laboratories have shown serious differences in interpretation of some of the textures seen in reacted and heated cokes. In an attempt to clarify this, CRL has initiated an inter-laboratory study in which coke samples provided by CRL will be examined by laboratories in several countries. It is hoped this will lead to improved techniques and more valid interpretations.

To support this work, CRL has recently completed a detailed comparative study of a number of coke samples from various countries and has also used these samples in high temperature studies, some of which are described in one of the Conference papers.

On a larger scale, a blast furnace raceway rig has been built at CRL, partly for studies of coal injection through the tuyeres and also for larger scale studies of the high temperature behaviour of cokes. Some results of this work are also included in a Conference paper. A smaller version of this rig has also been designed so that test oven cokes may also be tested by this technique. It is expected that this rig will reveal differences in behaviour of various Australian and overseas cokes.

Future research will continue along these lines, with the following major objectives:

i) to improve understanding of the behaviour of coke in the furnace and develop tests which better characterise this behaviour; and

ii) to develop reliable methods of predicting coke performance from coal properties.

It will also be necessary to continue to evaluate and, possibly develop, new techniques in cokemaking.

Current and future research at ACIRL is aimed mainly at improving knowledge of the coking behaviour of Australian coals and investigating reasons why they behave differently in some ways from overseas coals. New cokemaking techniques will also be evaluated where possible and new tests for coke will be assessed. Automated coal and coke characterisation will be a major aspect of this research.

Both the CRL and ACIRL programmes are receiving substantial support from the Australian Government through the National Energy Research Development and Demonstration Programme (NERDDP) and close contact is maintained between
the two laboratories to avoid unnecessary duplication of work.

Achievement of these goals will bring very significant benefits to BHP in coking coal utilization and will lead to more correct assessment of the qualities of Australian coals for export.

III. Sintering and Pelletising

1. Ore Resources

Prior to 1960, research studies in Australia were aimed at improving the quantity and quality of sinter that was being used by the Australian Steel industry. Very little interest was shown in the pelletising process.

In the late 1950's, large high grade hematite iron ore deposits were discovered in the Pilbara region of Western Australia which greatly increased the known reserves of Australian iron ores and allowed the Government export embargo on iron ore to be lifted. Developments in rail transportation and increases in the size of mining equipment meant that viable commercial exploitation of these new reserves could be commenced with the majority of the ore being consigned to overseas customers.

Overseas developments had shown that iron ore pellets were an attractive blast furnace burden material that could be transported over long distances with minimum size degradation. Some of the Australian iron ores were found suitable for the pelletisation process and pellet plants were installed at various locations during the 1960's to produce pellets essentially for the export market.

In parallel with this dramatic increase in the exploitation of Australia's iron ore resources, there has been an increase in the number and scope of research studies aimed at optimising the quality of sinter and pellets. The following is a review of the types of research undertaken and for convenience these studies have been separated into those applicable to sintering and pelletising.

2. Sintering

A major impetus was given to sinter research in Australia when the advantages of producing self fluxing sinter were demonstrated overseas. Studies using experimental sintering facilities showed that self fluxing sinters could be produced from Australian ores.30,31) Bogan and Worner30) showed that the three iron ores studied, two from South Australia and a dense hematite from Western Australia, had differing responses to sintering and produced different structures. The importance of sinter structure on sinter properties had been identified by Coe and Skinner.33)

As the result of these studies, a number of plant trials were carried out, and whilst the sinter plant operations were generally satisfactory, blast furnace operations tended to deteriorate. However at the Kwinana works, the combination of a modern sinter plant, which allowed the introduction of deep bed sintering practice, a coarse iron ore, and the type of fluxes used, yielded a fluxed sinter that gave a significant decrease in blast furnace coke rate and increased hot metal production.33) Following the successful introduction of fluxed sinter practice at Kwinana in 1972, further investigations assisted in the introduction of this practice at the Port Kembla34) and Newcastle Steelworks. One factor that was shown to have a significant effect on the microstructure, and hence sinter properties, of fluxed sinter was the size distribution of the ore feed, and to a lesser extent the size distribution of the flux.35)

To further improve the properties of sinter, particularly the high temperature characteristics, the use of higher magnesia contents derived from dolomite or serpentine has been implemented.36) The influence of alumina, derived from kaolinite gangue in the iron ore, on sinter properties has also been studied38) and it was concluded that sinters with constant quality could be produced over a sinter alumina range of 2 to 2.8%.

In all of these studies, the importance of sinter microstructure was confirmed37 and this has led to a technique that quantifies the mineralogical phases present using mineral phase point counting. Currently investigations are in progress to determine the mode of formation of the sinter structure. Initially, samples of iron ore were heated to various temperatures and the changes in microstructure determined.38) This work has been extended by examining the formation of silico-ferrite of calcium and aluminium (SFCA) using thermal conditions found in the sintering flame front. The influence of ore mineralogy on sintering is also being studied by Hamilton and colleagues at the Division of Mineral Chemistry, CSIRO, as a development from their work on pelletising studies.

Considerable research is being done on the mixing of the sinter feed materials and their granulation, to obtain good gas permeability in the bed of raw mix on the sinter strand. The selection of mix moisture has a significant effect on mix permeability39) and the moisture level required is strongly influenced by the iron ore types present in the sinter feed.40) The method of mixing the raw feed materials, in particular the fuel component, has been shown to be most important40) with a significant improvement in sinter productivity resulting from the addition of the coke fuel after the majority of granulation has taken place.

A collaborative research programme is in progress between BHP and the Division of Mineral Engineering, CSIRO, to develop a computer model of the sintering process. As part of this development, research is being undertaken to predict quantitatively the behaviour of particles during granulation, and the results to date are being presented at this meeting.41)

3. Pelletising

Even though the iron ore pellet plants in Australia were commissioned in the late 1960's and early 1970's, some pellet research had been in progress earlier. In the early 1960's, work had been undertaken to examine beneficiation of low grade jaspilite
associated with the high grade hematite ores in the Whyalla district of South Australia. The beneficiation involved converting the iron oxide in the jasperite to magnetite and producing a magnetite concentrate that would be suitable for pelletising. A plant was installed to produce magnetite from low grade iron ores in 1975. However, the rapid increase in oil prices in the mid 1970's made the process uneconomic.

An interesting development, which did not advance beyond smelting trials in a small experimental blast furnace, was the production of pellets produced from coal, iron ore and limestone fines. The Pilbara ores being pelletised contained more goethite than ores used overseas and this caused some limitation on pellet production rate until aspects of the drying part of the pelletising process firing cycle were fully evaluated by CSIRO, and modifications made to the pellet plants. Nicol and Adamia
d studied the influence of various types of bentonite binder on pellet drying rate and green pellet strength before and after drying.

A comprehensive series of studies into factors that affect the pelletising process and pellet quality has been undertaken by various Divisions of the CSIRO. Initially the effects of indurating conditions were studied and, with the assistance of microstructural analysis, the total effect of chemical and physical factors on pellet properties was determined. Frazer et al. produced pellets from nine types of iron ores and studied the effect of basicity on pellet swelling during reduction. They showed that maximum swelling occurred in the basicity range 0.2 to 0.8 for all the ores.

The results of these fundamental studies assisted in the formulation of mathematical models of the pelletising process. These models were applied to a straight grate pellet plant with considerable improvements in operating efficiency and have also recently been applied to the operation of both grate/kiln and vertical shaft furnace pellet plants.

The pellet plant installed at Whyalla in 1968 has been operated to supply pellets to overseas customers and also for the local steelworks. Trials were carried out to produce fluxed pellets with CaO/SiO₂ ratios up to 1.5 in 1970. Fluxed pellets could be produced when limestone was used as the flux and the heat input in the preheat part of the firing cycle was increased. Blast furnace operations using these fluxed pellets indicated an improvement.

As a result of overseas experience and pilot scale studies, the production of fluxed pellets using both dolomite and limestone as the fluxing materials was implemented at Whyalla in 1979 and these pellets now form up to 80 % of the ferrous burden. The results obtained confirmed that the addition of MgO improved high temperature characteristics, leading to improved blast furnace efficiency in terms of productivity and fuel savings.

4. Reduction of Iron Oxides

Sinter and pellets are produced to enable iron ore fines to be converted into a material that is easily reduced to iron. The physical and structural changes that occur during the reduction of iron oxides have been studied extensively. In Australia, the main emphasis has been on the behaviour of high grade pellets when being reduced under conditions that are applicable to direct reduction processes, rather than blast furnace smelting.

Fundamental studies by the Department of Mining and Metallurgical Engineering, University of Queensland, have examined the influence of reducing conditions and impurities in the iron oxide on the catastrophic swelling during reduction. This work has been extended to determine how different impurities influence the morphology of iron produced from wustite.

5. Future Trends in Agglomeration Research

Modern blast furnace technology requires high quality sinter and this has led to intensive research into the sintering process. Studies examining the reactions and changes in microstructure that take place during sintering will lead to improved sinter properties, as the result of optimising the amount of bonding phases. The amount and type of bond is controlled by the reactivity of the iron oxides, fluxes, gangue components and additives. Also the particle size and distribution of the reacting particles in the granulated raw sinter mix have a significant effect on the amount of fuel that is required to generate the thermal conditions which produce the required bonding liquids.

These sintering reaction studies will assist in the development of computer models of the sintering process, which should lead to improvements in the operating efficiency of sinter plants, just as computer models have improved control of the pelletising process.

Past research has indicated the strong influence of iron ore mineralogy, chemistry and physical properties on the sintering process. Besides the high grade hematite ores that are currently being exploited, Australia has an abundant supply of hydrated iron ores. The introduction of hydrated ores in pelletising caused some difficulties which were readily overcome with process changes. Preliminary studies have shown that, for sintering mixes containing a significant proportion of hydrated iron ores, only minor changes are required to the operating conditions to produce good quality sinter.

In the case of pelletising research, it is considered that the only scope for further improvements in production for the blast furnace lies in process improvement by means of computer models and maximising fuel cost efficiency by including carbonaceous materials in the pellet feed. It is considered however that the production of high grade pellets for the production of direct reduced iron will require further development, in order to optimise pellet properties for each direct reduction process.

In the longer term, new types of sinter, pellets, or other forms of agglomerate may have to be developed.
for new processes which will aim to convert iron oxide to metal more efficiently than the currently available processes.

New techniques, e.g., Mossbauer spectroscopy, are being developed which may prove to be of use for the characterisation of iron ores, sinters and pellets. This is a nuclear spectroscopic technique which is able to give very accurate quantitative assessment of both the relative proportions of iron-containing phases present and their structures. Mossbauer analysis has recently been applied to a range of Australian iron ore minerals. The relative abundance of hematite and goethite was determined, and the possibility of aluminium substituting for iron in these minerals investigated.

It has been found in overseas studies that the amounts of the iron phases present in sinter are able to be determined, giving results comparable to those obtained by point counting. The variations in the composition of the SFCA are not able to be detected in the spectra, but significant changes in magnetic stoichiometry with magnetite content have been observed. Mossbauer spectroscopy has been applied to the study of iron ore pellets, as well as a number of other materials relevant to ironmaking, and it seems likely that it will play an increasing role in future steel industry research activities.

IV. Ironmaking
1. Early Blast Furnace Studies

In the 1950's and early 1960's, Port Kembla blast furnace performance was amongst the best in the world, largely because of the quality of raw materials. The local coke was strong and low in sulphur, though high in ash, and the lump ore was of high grade. The necessity for other ironmakers to use pre-agglomerated ores, which gave them the ability to match the feed characteristics to the furnace operation, lent impetus to more detailed blast furnace studies in Australia.

Significant research in ironmaking commenced in Australia after the establishment of CRL in 1956, with the earliest work relating to slag studies, and an innovative approach to studying gas flow in the blast furnace using a mercury tracer, developed in collaboration with the Carnegie Institute of Technology and the US Bureau of Mines. Other work was carried out on the control of sulphur, alkalis in blast furnace slags, and the statistical relationship between manganese and sulphur in hot metal. Henderson continued CRL's work on slags to the mid-60's and produced a series of publications on transport phenomena in lime-silica-alumina melts. At the same time, work commenced on the degradation of ferrous burden materials in the blast furnace stack, an important area at the time supporting the change of company practice to substantial usage of sinter.

Prior to the successful introduction of oil injection practice at Newcastle and Port Kembla Works in 1962, Howarth developed a theoretical analysis of the effects of oil on coke replacement, based on a heat balance around the raceway. A later paper detailed the results of fuel injection practice (various grades of oil and coal tar) at the works centres, identified the effect on injection levels of poor coke quality at Newcastle Works and discussed atomisation of fine coal into an injection air stream.

From 1965, the major work related to heat and mass balance modelling of the blast furnace process. This was a natural outcome of the need to establish a more scientific approach to the overall blast furnace process, at a time when computer technology was rapidly developing.

For the first half of the 1970's, heat and mass balance modelling and feedback control of the blast furnace were the major research areas. This culminated in a trial at Newcastle Works in 1973, which showed that computer control led to a significant increase in both productivity and hot metal silicon control. Important contributions to the understanding of blast furnace operation during this period were theoretical studies on blast furnace operation with reducing blast (via top gas recycle with carbon dioxide removal by scrubbing), a theoretical analysis of reduction in the blast furnace, and a study on the significance of penetration and flooding (the first study at CRL into raceways). In addition to this work on blast furnace mathematical models, studies were carried out on CO and H2 utilisation in the blast furnace (with relative values being developed for alternative blast injectants).

Novel uses for blast furnace slag received considerable attention. Richards and co-workers undertook a substantial programme to produce building products from cerameal glass, made by modifying blast furnace slag with silica and fluorospar.

There was relatively little research into engineering matters. However, considerable effort was put into the optimisation of design and production of evaporatively cooled stoves.

2. Current Research

The basis of current ironmaking research in Australia was laid in the mid 1970's, and resulted from the following factors:

i) The development of a more fundamental understanding of the blast furnace process from quenched furnace studies (particularly in Japan). These studies resulted in the widespread adoption of the cohesive zone concept, which led to blast furnace gas distribution modelling and a better understanding of the ferrous burden and coke properties important in the blast furnace.

ii) The recognition that gas distribution, raceways, hearth liquid drainage and raw material characteristics basically control the blast furnace process (within the overall constraints of heat and mass balances). Therefore a broader research programme covering these aspects was required to provide appropriate advice to blast furnace
operating groups.

iii) The increased availability of computers in operating departments and of technical personnel in Technology and Development groups working directly with operating departments. The latter are essential if models and techniques developed by research personnel are to be implemented in production.

Consequently, most of the work has been in areas which were also under rapid development in Japan over the same period, namely:

- gas distribution,
- hearth liquid drainage, and
- raceway studies (including coal injection).

The origins of most of the current research can be traced back to Burgess and co-workers at CRL but it now involves personnel at the BHP Works and in departments at the Universities of New South Wales, Newcastle and Queensland. However, Standish and co-workers at the University of Wollongong had already initiated research into many chemical engineering aspects of blast furnace operation. These studies included burden permeability, with consideration being given to coke/ore interfacial pressure losses under static and dynamic conditions, laboratory scale studies of liquid hold-up above raceways in static packed beds and theoretical aspects of stack injection.

Initial work on gas distribution at CRL involved determining the pressure losses in uniform and layered packed beds of blast furnace raw materials, with attention being paid to the interfacial problem. It was found that the pressure losses could be predicted by the high Reynolds Number form of the Ergun equation. The experimental data were used in a mathematical simulation of an idealised cohesive zone to predict gas flows towards the furnace walls, and pressure drops at the walls, as a function of height. Later work examined the effects of cohesive zone shape on gas flow through the coke slits and, using data from above and below burden probes, predicted the cohesive zone shape, the ore to coke ratio, gas flow distribution, and temperatures and compositions of both gases and solids in the upper part of the blast furnace. The further extension of this work enabled the location of the cohesive zone root to be predicted from furnace pressure profiles and it also compared predicted root levels, using both the pressure tapping and stave temperature methods, with in-burden probe temperatures over a period of changing operation of Port Kembla No. 5 BF. Currently these models are used for investigative purposes at Port Kembla Works. Efforts in the recent past at Port Kembla Works to achieve gas distribution control have been described by Warner and Lowcock.

Considerable use has been made of a full scale replica of the bell-less top on No. 5 BF, Port Kembla in developing and refining a model of burden distribution, and also for optimising chute design.

Work on hearth liquid drainage commenced in 1979 at CRL, from which a very fruitful collaboration developed with Dr. Pinczewski and co-workers in the Dept. of Chemical Engineering, University of NSW. In the period to date, this work has progressed rapidly from experimental and theoretical studies on one liquid in a 2D packed bed (with and without areas of differing voidage) through two liquids in a 2D packed bed, to one liquid in a 3D packed bed. Work is currently in progress on the mathematical modelling of two liquids in a 3D packed bed. When this is completed, heat transfer effects will be incorporated and furnace trials initiated.

Raceway studies commenced in 1980, with the prime interest being to develop an understanding of the effects of coal injection on raceway dynamics. A review of raceways was presented by Burgess at the International Hearth and Raceway Symposium in 1981. The approach taken was similar to that in Japan, namely experimental measurements on the hot model of a raceway/coke combustor; in the CRL work, an electrical air heater is used to ensure that blast chemistry could be controlled to simulate blast conditions in an operating furnace. Both visual and temperature-measuring fibre optic probes were used with a gold coated window being used to reduce significantly the temperature at the tip of the optical fibre. To date, various aspects have been examined, including:

- coal combustion in the blowpipe;
- conveying of coal, with the aid of a powder dispenser utilising a fluidised bed for close control of flowrate;
- raceway geometry; and
- variations in coke properties.

Various chemical aspects of blast furnace operation have received attention from time to time, such as the role of magnesia in slag formation and the control of hot metal chemistry. The application to furnace control of more fundamental studies of sulphur and silicon partition is described elsewhere in this conference.

Recently, finite element methods have been used in heat transfer calculations to predict the hearth erosion profile in operating blast furnaces. The extent of likely metal penetration into the hearth is assumed to be the position of the 1 150 °C isotherm, and this is calculated from a number of considerably lower temperatures measured at thermocouples located within the refractories constituting the hearth. For example, the calculated temperature distribution in the hearth of Port Kembla No. 5 blast furnace corresponding to actual temperatures measured in the refractories in March 1983 is shown in Fig. 2.

Although these isotherms are only approximate due to errors in thermocouple location and readings, and to unknown variations in thermal conductivity with time and temperature, this technique enables trends in hearth erosion or deposition to be detected. For example, a decrease in hearth refractory temperatures at Whyalla No. 2 blast furnace, following a period of reduced intensity of operation between November 1982 and April 1983, has been interpreted as a build-up on the hearth wall of about 100 mm.

This computational technique has already proved...
of value in understanding operating furnaces and its accuracy can be improved in future by comparing the lines of blown-out hearths with the calculated profile, and by locating thermocouples more effectively when re-building furnace hearths.

3. Future Developments

The characterisation and preparation of the feed materials, coke and sinter, have been discussed as processes separate from the blast furnace. This is not really so; one of the exciting anticipated developments is the closer identification of critical feed properties, from research into furnace processes, and, hand in hand with this, the ability to meet these feed specifications, which could be gained from greater understanding of raw material characteristics and treatment processes.

We appear to be close to determining the basic characteristics required of coke through study of the reactions that coke actually undergoes, as indicated by comparison with cokes extracted from the furnace and the raceway rig. Laboratory and mathematical modelling studies of raceways will in future be carried out by Dr. Burgess in the Dept. of Chemical Engineering, University of Queensland, while CRL will continue studies of coal combustion kinetics (in collaboration with the Dept. of Chemical Engineering at the University of Newcastle), raceway geometry as a function of a wide range of blast parameters, and coke breakdown around the raceway. In this work, the behaviour of a number of Australian cokes will be studied, and compared with a high quality Japanese coke which has been obtained for this purpose.

Current mathematical models of the blast furnace tend to be localised to one or two regions, e.g., pressure drop in the stack and cohesive zone. Work has already begun to build an integrated heat, mass and momentum transfer model of the blast furnace. This should enable, for example, a closer examination of the factors affecting cohesive zone shape and location, which should throw new light onto the properties required of the burden materials. This information can lead to improvements in their production, hence optimisation of the whole ironmaking process.

V. Conclusion—The Future

Although many have forecast the demise of the ironmaking blast furnace, particularly in the last decade, there is no doubt that the blast furnace will continue to remain the major process for producing iron, at least up to the turn of the century. Direct smelting, using coal and oxygen, appears to be the most promising challenger, but to develop such processes to a scale rivalling the blast furnace would take at least ten, and more probably 15~20 years.

The recent rationalisations of the iron and steel industry around the world have resulted in the removal from service (and often demolition) of the highest cost ironmaking units. In the current market situation, this increases the difficulty of introducing a new process in developed countries. In the lesser developed countries, which have a growing need for iron and steel products, new process development is fraught with difficulties.

Scrap based processes have made considerable progress due to the current lower scrap prices; however, scrap (particularly with low tramp element levels) is a limited resource, and the increase in continuous casting facilities is decreasing the amount of internally generated scrap. When a significant market upturn occurs, some of the high cost ironmaking units will be recommissioned (if there is sufficient coking capacity) and crisis planning will commence, to evaluate the economics of a new blast furnace vs. coal-based direct reduction or possibly direct smelting, if sufficient development work has been completed. Because of the massive levels of investment for a new blast furnace (and associated facilities), there is need for a continuing research and development programme, particularly on direct smelting, to ensure that economic alternatives exist.

Research on the blast furnace ironmaking process as we know it today, and its raw materials, is within sight (less than 5 years) of being substantially “complete”. While recognising that no area of research is ever truly complete, within this time frame we will have overall models of the blast furnace which take into account all gas and liquid flows, state of burden components at any point in the furnace, accurate prediction of hot metal quality, and a good knowledge of the coke and sinter quality factors which affect blast furnace performance. An improved knowledge of coal and iron ore blending will be available, and a major question for the future (if blast furnace technology is expected to remain dominant for 30~40 years) will be whether or not to develop a continuous, low pollution cokemaking process. In hindsight, earlier attempts at such processes were handicapped by a lack of knowledge regarding coke quality requirements in the blast furnace. The new knowledge which is now emerging will overcome this problem.
While research into the subjects of this meeting will continue, recent initiatives have been taken in Australia to increase our effect on:

Direct Smelting — assessment of overseas developments, evaluation of suitability of Australian iron ores and coals, with the potential for process development (perhaps in collaboration with overseas groups).

Direct Reduction — assessment of overseas developments, evaluation of the suitability of iron ores and coals, and fundamental reduction studies.

Plasma smelting is not envisaged for ironmaking in Australia, but could be of interest for ferroalloy production.

Because of the relatively small production of blast furnace iron in Australia, the funds and manpower available for ironmaking research in Australia are also limited. Our research therefore does not cover the whole range of blast furnace phenomena, and we gain a great deal from close contacts with research work in other countries, and the exchange of ideas in conferences such as this Joint Meeting in Japan. I trust that the Australian papers presented at this conference will give a representative picture of the research work currently being pursued in Australia, and lead to profitable discussion of the very important subject of ironmaking.

REFERENCES