THE INCREASING ROLE OF DIRECT REDUCED IRON (DRI) IN GLOBAL STEELMAKING

Francois Grobler

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Declaration

I declare that this project report is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Signed: _____

Date: 25 MAY 1998

Place: JOHANNESBURG

DEDICATION

This dissertation is dedicated to my father, Nicolaas Johannes Grobler - who taught me to be inquisitive.

The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them - Sir William Lawrence Bragg 1890 - 1971

(In A Koestler and RJ Smithie's Beyond Reductionism 1968 (London: Hutchenson))

Caminante, no hay camino
Se hace camino al andar.
Traveller, there is no path,
Paths are made by walking
(Theme of popular Latin American song)

" There are projections of world-wide shortage of scrap at some time in the not-too-distant future, by the year 2000, 2010 or 2020" *Kenneth Iverson, Nucor Chairman and CEO*

"There's room in the steel industry for a blend of both more traditional and also the newer lower-cost alternatives" *John Mayberry, Dofasco President and CEO*

" I believe that many of these efforts will result in production economics that will allow the producer to manufacture iron units suitable for a variety of post-reduction processes at costs less than US$ 100 per ton on a fully loaded basis." *Keith Busse, President of US mini-mill Steel Dynamics on alternative ironmaking processes.*

Abstract

This report gives an overview of the role and use of directly reduced iron (DRI/HBI) used in the electric arc furnace (EAF) steelmaking route as a substitute to the traditionally favoured ferrous scrap. A comparison of the main steelmaking technologies showed that the electric arc furnace (EAF) has emerged as the preferred route for producing steel since the early 1900's. Due to its lower costs, scale and flexibility, it is expected to outgrow the conventional steelmaking method based on the blast furnace and basic oxygen converter in the next century.

A look at historical steelmaking patterns showed that electric arc steelmaking has relied almost entirely on ferrous scrap as its primary feedstock up to the present time. This traditionally low-priced commodity has in the past fulfilled the steelmakers' criteria in terms of quantity and quality. Investigation of the current situation, however, showed the mounting pressure on high quality scrap more recently, with the subsequent rise in the price as well. The most important factors contributing to the tightness in scrap availability proved to be the increasing popularity of the EAF, and especially the "mini-mills", accompanied by improvements in technology such as continuous casting (CC) and near net shape casting (NNSC). This has forced EAF steelmakers to consider other substitutes such as direct reduced iron (DRI) and pig iron, not just as an alternative to scrap, but as an effective blending material to reduce residual elements in the scrap melt. A comparison of different metal charges in the EAF showed that the blending of DRI with scrap enabled the steelmaker to utilise the more abundant, less expensive, lower quality scrap grades, whilst maintaining quality requirements.

A study of the trends in DRI technologies indicated that the gas-based technologies, such as Midrex and HyL, still dominate the market for DRI, as they have in the past, enjoying economies of scale and other favourable cost advantages. It appears as if coal-based processes have traditionally encountered constant economical problems, which disabled them in competing with those based on gas. Another trend of the past was the high proportion of captive DRI production, compared to the very limited amount of merchant product available on the market. That was the status quo in past years.

The present situation seems to be different. It appears as if that current problems with scrap availability and quality is actually paving the way for the use of DRI. Prices asked for good quality scrap are on the way upwards as steelmakers frantically search for low-residual, reasonably priced iron units. This has lead to a multitude of new DRI projects, either being built, planned, or considered, aimed at fulfilling this demand. Some of the new projects are based on older, tested technologies, but the amount of new projects based on newer, customised technologies that utilise low-cost fines, non-coking coal and other incentives to minimise costs seems to be increasing as well. Another change in the past trend lies in the large proportion of the new non-captive capacity that will come on stream, specifically aimed at the merchant market.

The most critical determinant for such a merchant DRI project is its location. The strategic positioning of it in terms of its raw materials i.e. iron ore, natural gas, coal etc., as well as its location with regard to the potential market, will determine whether it will be competitive or not. Operating costs are considered and compared to determine the competitive advantages with regard to different location- and technology options.

Additionally, it seems as if the successful DRI producer of the future will be the one who, apart from optimising its position, will minimise cost by utilising low-cost iron ore fines, cheap low-grade coal, gas recycling and many other cost cutting incentives vigorously explored by all DR technology producers in recent years.

In summary, there proves to be an increasing need for DRI and other scrap substitutes in the steelmaking industry and such projects will definitively have a market in the future, but care must be exercised in the decision on the location, and other cost-contributing determinants of such facilities. Another potentially dangerous situation stems from the fact that this "hungry" market, although currently undernourished, is ultimately not insatiable, and care must be taken to prevent the development of a massive oversupply, which could cause imbalances in the market again. In any event, with all the new merchant product coming into the market, it seems evident that DRI will develop its own spot market, and competition between different DRI technologies, as well as with scrap will become fierce in the future.

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CHAPTER 1 INTRODUCTION

1.1 Steelmaking and the scrap problem

Steelmaking has been around for many centuries. Even in the ancient and medieval times, steel was regularly produced although in small quantities. This was done by heating and manipulating iron ore at temperatures below the melting point of iron, and t. en going through a laborious ritual of reheating and manual reworking to eventually end up with a useable piece of steel.

The interest in producing iron directly from the ore in a solid state without having to melt it at high temperatures already existed in the early 19th century. The technical and economic problems experienced in those days, however, prevented direct reduction (DR) processes from competing with the indirect process of first producing pig iron via the blast furnace, and then refining it into steel. Consequently, the interest in DR processes began to decrease.

During the mid-1800's, processes started developing that produced steel by oxidising pig iron to remove unwanted carbon and silicate material. These improvements in the conventional methods increasingly simplified steelmaking and resulted in escalating steel production. So it came that the blast furnace took over the role of reducing iron ore, and in much larger quantities at that. The impurities contained in the molten iron could be removed easily although a high content of carbon remained.

Since the early 1900's, however, another significantly different method of producing steel was being developed. The electric arc furnace (EAF) emerged, using steel scrap as the basic charge and having little reliance on iron ore. This steelmaking method, although it had a late start, has become increasingly popular among steelmakers, especially considering its lower capital investment costs and smaller scale to name but a few advantages.

Due to production efficiencies such as continuous casting and near net shape casting (NNSC), as well as the entrance of EAF's into the arena of large scale, higher quality products traditionally occupied by the conventional blast furnace/ basic oxygen converter, more and more pressure is exercised on the available high quality, low-residual scrap supply, the main source of metallics in EAF steelmaking.

This has increasingly forced steelmakers to consider other sources of low-residual metallics, and more specifically, direct reduced iron (DRI), as potential feedstock of EAF steelplants.

This chapter highlights the ferrous industry and focuses on the two main steelmaking technologies currently utilised i.e.: the blast furnace/ basic oxygen converter (BF/BOF), and the electric arc furnace (EAF).

1.2 The Ferrous Industry

The steelproducing or ferrous industry consists of:

- the **mining industries** supplying raw material inputs of iron ore, coke and limestone,
- the **iron and steel industry,**
- **steel fabrication industries,**
- and the **steel scrap processing industry** which collects, separates, cleans and grades discarded steel scrap for recycling to the steelmaking industry.

The five major groups of activities that characterise conventional steelmaking are:

- coking,
- sintering,
- ironmaking,
- steelmaking,
- final rolling and finishing.

Coking - During coking, coal is heated in the absence of air driving of a portion of the non-carbon constituents of coal (volatile matter, water, and sulphur) as a gas. The product is coke, which then principally consists of some 90 per cent carbon. The remainder is ash and sulphur. Coke is used as fuel and source of carbon monoxide in the ironmaking process (blast furnace), while the gas that is driven of from the coal could be processed to remove saleable by-products (oil, sulphur, tar, phenol, ammonia etc.).

Sintering - Sintering is the process that agglomerates fine ore particles into a porous mass for charging to the blast furnace. This is accomplished by the application of heat from the combustion of coke mixed with an ore and flux (limestone) charge. Sintering was not just developed to make better use of iron ore fines and recovered blast furnace dust, but it also drives off some of the impurities contained in the ore (e.g. sulphur) into the air.

Ironmaking - Molten iron is produced in the **blast furnace** by the reduction of iron ore. Ores and processed iron -bearing materials, such as sintered ore and flue dust, are charged into the top of the furnace in combination with predetermined amounts of limestone and coke. At the bottom of the furnace, preheated air is blown into the charge to burn the coke in the descending mass. Gas from the burning coke (mostly carbon monoxide) is responsible for most of the reduction as the stock of materials descends countercurrently to the flow of gasses. The acid part of the ores fuses with the lime in the limestone and the other bases, and creates a slag that floats on the molten iron and is frequently drawn from the furnace. The molten iron is thus separated from the non-metallic part of the ore as well as impurities such as sulphur and manganese.

Steelmaking - The blast furnace is designed to reduce iron oxides and to separate the resulting iron from impurities in the ore, whereas the making of steel from molten iron or scrap, primarily involves removal of relatively small amounts of certain impurities from the metallic charge through oxidation. Molten iron in particular is saturated with carbon and contains undesirable amounts of silicon, manganese,

phosphorous, and sulphur which are mostly removed in the furnace slag. Currently the leading furnace types used in the production of steel are the **open hearth furnace (OH), the basic oxygen converter (BOF)**, and **the electric arc furnace (EAF).**

McGannon[58] explains how, after the molten steel had attained the desired chemical composition in the steelmaking process, it was traditionally tapped from the furnace into a **ladle** from where steel was poured into tall, usually rectangular moulds where it solidified to form **ingots.** Ingots were then reheated to a proper uniform temperature after being removed from the molds, and rolled or forged into shapes known as **blooms, billets and slabs** which are referred to as **semifinished steel (semi's).**

Currently, increasing quantities of semi-finished steel are being produced by pouring liquid steel into the top of open-bottomed molds in **continuous-casting machines** where it solidifies and is continuously withdrawn from the bottom of the molds in long lengths of the desired shapes.

Blooms, billets and slabs are referred to as semifinished steel because they form the starting material for the production of finished steel products by mechanical treatment (hot rolling, cold rolling, forging, extruding etc.). These include **bars, plates, structured shapes, rails, wire, tubes and coated and uncoated sheets** all in various forms and sizes required by users of steel.

1.3 Steelmaking

The three furnace types currently used in the production of steel are the **open hearth furnace (OH)**, the **basic oxygen converter (BOF)**, and the **electric arc furnace (EAF).**

1.3.1 The Open Hearth Furnace

In the open hearth furnace a long, shallow charge bath containing iron-bearing materials is heated by radiation from a flame. The fuel may be natural gas, coke oven gas, fuel oil, coal tar or a combination of these. The choice of fuel will influence the sulphur dioxide generation per ton of steel produced (McGannon[58]).
Oxygen could also be introduced for combustion, air enrichment and for removal of carbon from steel. If not, then most of the required refining oxygen will be provided by iron ore included in the charge.

The open hearth furnace is the most flexible of the steel furnaces in its ability to handle different proportions of scrap and hot iron. The range can vary from 70 per cent hot iron and 30 per cent scrap, to 50 per cent hot iron and 50 per cent scrap, but the furnace can be used with 100 per cent cold metal as well.

1.3.2 The Basic Oxygen Furnace

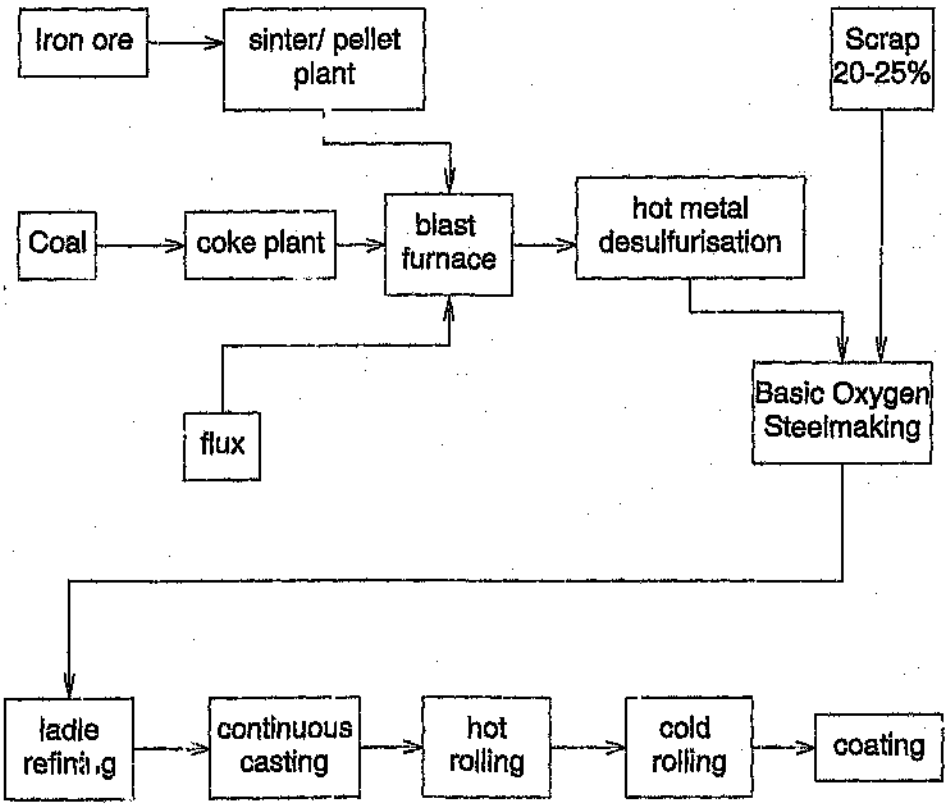
The conventional steelmaking method currently used is the **blast furnace/ Basic Oxygen Converter** where hot metal is first produced from iron ores and then refined into liquid steel in the converter (figure 1.1)

In this process, nearly pure oxygen is introduced from above the surface of a bath of molten iron contained in a refractory brick-lined cylindrical furnace. The **characteristics** of this process are:

- the use of oxygen as sole refining agent,
- dependence on molten iron and the oxidation reactions as the only sources of heat, implying a lower tolerance for cold metal,
- achievement of rapid refining of the charge,
- generation of a large amount of red fume or dust.

The process is less flexible than the open hearth in its ability to use cold iron and scrap steel in the charge, due to the nature of its heat balance. The range of alternative combinations that can be introduced varies from 70 per cent hot metal and 30 per cent scrap to 90 per cent hot metal and 10 per cent iron ore. Higher scrap use rates are possible in furnaces modified for scrap pre-melting using natural gas injection (McGannon[58]).

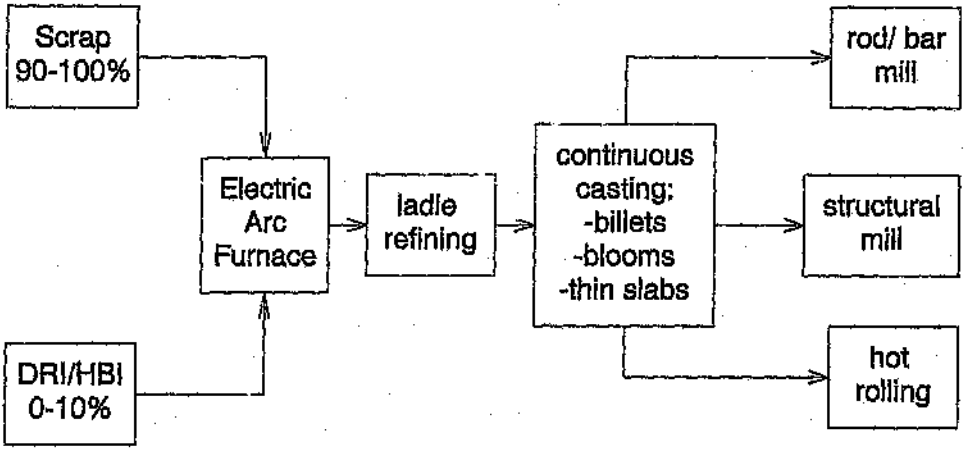
Figure 1.1 Simplified flowdiagram of conventional integrated Steelworks



1.3.3 The Electric Arc Furnace

In the electric arc furnace (EAF) route scrap, or direct reduced iron (DRI), is melted into liquid steel (figure 1.2).

Figure 1.2 Simplified flowdiagram of Electric Arc Steelmaking



Because of advantages such as **low capital investment, shorter installation period, ready-made market for products** and **suitability for lower tonnage production**, there has been a rapid growth of arc furnaces all over the world. Statistics published by the International Iron and Steel Institute (IISI) show that out of a total world crude steel production of 756,1 mt in 1995, 249,5 mt (33%) was contributed by the EAF process, 500 mt (66%) by the BOF and almost none by the OH process.

The source of heat in the electric arc furnace is electric power introduced via graphite electrodes positioned above the cold charge producing an arc which melts the scrap. Refining takes place due to a combination of the heat developed by the electrical resistance of the molten metal and the heat radiated from the arc (Peters[75]). As a principal source of refining oxygen either oxygen injection or an ore charge may be used.

One of the electric arc furnace's characteristics is its relatively inflexible ability to utilise molten iron in the charge. It is in essence a **100 per cent cold metal** user meaning in practical terms that it essentially uses 100 per cent scrap.

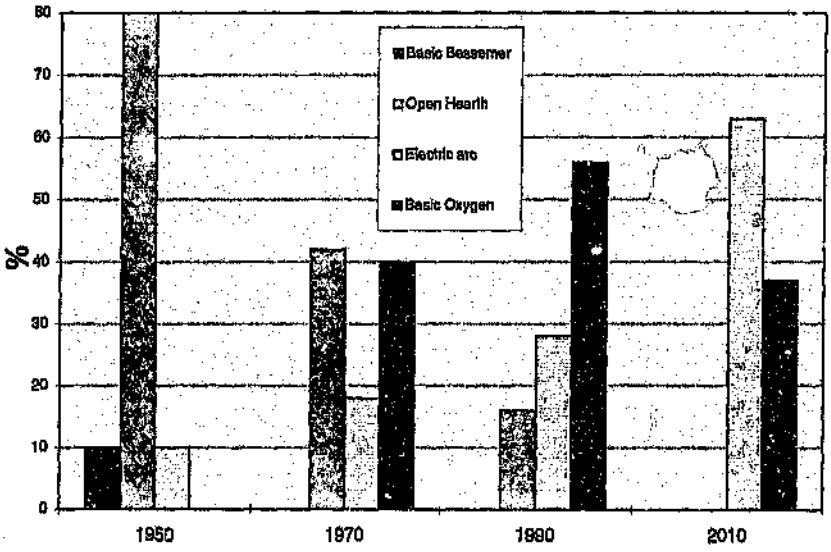
The electric arc furnace does not require supporting coke ovens, sinter strand and blast furnace facilities. Instead, the relative costs of fuels, scrap and other iron units will determine this technique's economic advantages or disadvantages.

1.4 Blast furnace/basic oxygen converter (BF/BOF) vs electric arc furnace (EAF)

The trend during the last twenty years, after the extinction of the Bessemer process, has been a gradual decline of the OH process and development of BOF and EAF steelmaking.

Figure 1.3 shows that both oxygen steelmaking and the electric arc route have become increasingly popular, accounting for between 80 and 90 per cent of steel production, while the open hearth technology seems to be disappearing.

Figure 1.3 Steel production by process



Over the later half of this century, oxygen steelmaking has rapidly progressed. This steelmaking route currently accounts for two thirds of world steel output. It exhibits a high degree of maturity regarding process metallurgy, process control and productivity as well as a high quality product.

In comparison, there has been a larger increase in the EAF share compared to the BOF in recent years. In developed and developing countries EAF's accounted for 33 to 34 per cent of steel production. According to projections for 2005 to 2020, the share of EAF steel in Europe is expected to go up to 63 per cent from the existing 32 per cent (figure 1.3).

Within the past twenty years, the basic arc furnace process grew by leaps and bounds from a specialised tool for making alloy steels or steel for casting on an interrupted cycle, to a large scale steel production unit for ingots or continuous casting machines.

1.5 Disadvantages of blast furnace/ basic oxygen converter

The biggest disadvantages of the blast furnace/basic oxygen converter route compared with electric arc steelmaking, are the **high investment costs** and **lower flexibility**. Brahma and Boom [13] state that electric arc furnaces of almost any size can be made (1 ton to 400 tons), but oxygen steelmaking converters of less than 30 tons are not economical because the cost of the oxygen plant has to be considered. Such big installations, where the smallest economically viable size is around 2 to 3 million tons per year, have a very limited adaptability to fluctuating market conditions. Rose and Walden [82] say that, additionally, they require costly burden preparation and are dependant on coke as reductant and fuel.

Therefore, it is expected that oxygen steelmaking will find it increasingly difficult to compete with the EAF, which uses scrap or direct reduced iron (DRI) as raw materials, and other processes such as smelter reduction, especially seen in the light of growing environmental concerns.

1.6 Advantages and disadvantages of using the electric arc furnace

Advantages are:

- **Independence from hot metal**; the "natural" charge for the basic arc process is scrap with coke or cast iron (pig iron) as recarburizer, or DRI.
- **High productivity** (20 to 80 tph); two furnaces can keep a continuous caster going in long strings of heats without interruption - if it takes 1 hour and 20 minutes to cast a heat, two furnaces, each tapping every 2 hours and 40 minutes will keep one caster going without interruption, only changing an empty ladle on the casting machine for a full one.
- The above possibility, coupled with the relatively **low capital cost** of the arc furnace/ continuous casting combination, made possible the advent of the **common mini-mill.**
- The furnaces are always of the tilting type allowing for **easy removal of the slag.**
- The **heat is well concentrated** as radiation from the arc and charge resistance. As a result, **control of the temperature** is easy and precise and the **thermal efficiency high**, especially because there is no combustion air passing through the furnace, the arcs being the sole source of heat; high temperatures can be obtained with ease, limited only by refractory wear.
- Because of the absence of air, it is possible to obtain non-oxidising, actually **reducing conditions**, thus making possible highly efficient desulphurisation, especially at high temperatures.
- As a result of the possibilities of refining under neutral or reducing slags, the oxidisation of heats can be kept low, thus ensuring **minimum oxidation losses** of ferro-alloys. For the same reason, large amounts of ferro-alloys can be added to the furnace while maintaining arc heating, making possible the **production of high alloy steels.**
- The furnaces can be **easily shut down and started up** without major damage to the usual refractories, thus making it possible to **schedule operations** for one or two turns per day only, week-end shutdowns etc.

- Because of the absence of voluminous excess air and combustion gasses, **dust cleaning installation is relatively compact but necessary.** A fair amount of dust is generated especially from poor-quality scrap.
- Since the tap temperature, tap time, and steel chemistry are well-controlled, it is possible in multi-furnace shops to make large ingots for **special forgings** exceeding the capacity of a single furnace. By timing several heats to tap in rapid succession and pouring them into one mold, as many as five heats of the same grade can be used to make a 200-ton casting.

Three **disadvantages** should be recognised:

- There is a **heavy dependency on scrap prices,** since normal operations call for a 100 per cent scrap charge.
- There is **susceptibility to steel contamination by residual elements** contained in scrap. While some unexpectedly high copper, nickel or chromium melts can be often tolerated, or even occasionally utilised by making corresponding low alloy grades, high tin melts, such as commonly obtained from detinned or city incinerator scrap, result in severe losses because of surface cracking of the steel. This problem can be **reduced by using direct reduced iron.**
- There is a tendency toward **absorption and retention of hydrogen and nitrogen,** the former being highly detrimental to high quality steels and the latter is for steels intended for flat products (sheet and strip).

1.7 Mini-mills

The US mini-mill revolution started 30 years ago, when entrepreneurs coupled a **scrap-based electric arc furnace (EAF)** with a **continuous billet caster and rolling mill,** producing rebar. As a business strategy, mini-mill operators were committed to flexibility, efficiency, and most importantly, low cost.

In the 70's and 80's, the scrap-based mini-mill industry was developing at a rapid pace in the U.S.A. Meanwhile, development of the integrated mini-mill industry was progressing mainly outside the U.S.A. An **integrated mini-mill** couples direct reduction technology with the EAF mini-mill techniques. Integrated mini-mill operators discovered that an EAF melting operation with 60 to 100 per cent continuously charged scrap substitutes was simple, highly predictable and produced exceptionally clean steel.

In contrast to the capital intensive coke oven/BF/BOF complexes of the past, integrated mini-mill facilities could be economically built and operated at capacities as low as 0,5 mt per year due to their relatively low cost, flexibility and efficiency at relatively low production rates. This allowed the steelmaker to gradually build up capacity in small increments.

1.7.1 Evolution of the mini-mill

Some of the principal reasons behind the rapid evolution in mini-mills are:

- the traditional **availability of scrap** at a relatively **low price** - this scenario is currently somewhat different,
- the **low capital cost** of the mini-mills - the scale is very much **smaller** than the minimum economic size of an integrated plant,
- the **flexibility** of such plants with low capital cost, limited manpower and metallurgical flexibility (an EAF is far more suitable for "stop and go" production than the complicated line of coke ovens + ore preparation + BF +BOF) - production can even be tailored to take advantage of lower off-peak powercosts (eg. in Tokyo, Shanghai)
- the important **technological development** underway in EAF and NNSC (near net shape casting) compared to the mature aspect of the processes of the conventional iron and steel plants.

Without doubt, certain facets of an integrated plant must be less flexible than those of a mini-mill. Long term contracts for iron ore and coal supplies do remove some flexibility but also provide a measure of security of supply that no integrated plant can do without. Also, there are many more operations involved in an integrated plant eg. the preparation of raw materials, such as coke ovens, sinter plants etc. This reduces the freedom of action to some extent.

1.8 The future for EAF steel

- On a global scale, the EAF route seems to have a bright future as long as there is adequate **availability of good quality scrap** in industrialised countries.
- Also, the **environmental pressure** is growing strongly around the world against integrated plants based on coke.
- Recent **technology and process advances** (e.g. DC arc furnace) have taken place, opening the EAF route to the market for flat products. **Flat rolled sheets,** and **high quality rods and bars** are now produced routinely in the electric arc furnace. Much of this is accomplished with 100 per cent scrap charging, coupled with extensive refining and precise control over the melting cycle. The scrap preferred is the best high quality, low residual scrap available.

For an EAF steel producer to make good steel, he needs **good iron units.** This has always meant purchasing quality scrap and then carefully selecting and grading it before it is charged into the furnace. Some steel applications are not as difficult or demanding as others. However, with the more modern furnaces and mills, the electric arc furnace product is entering the higher quality product ranges historically produced by larger integrated plants which necessitates the use of high quality scrap.

CHAPTER 2: FERROUS SCRAP

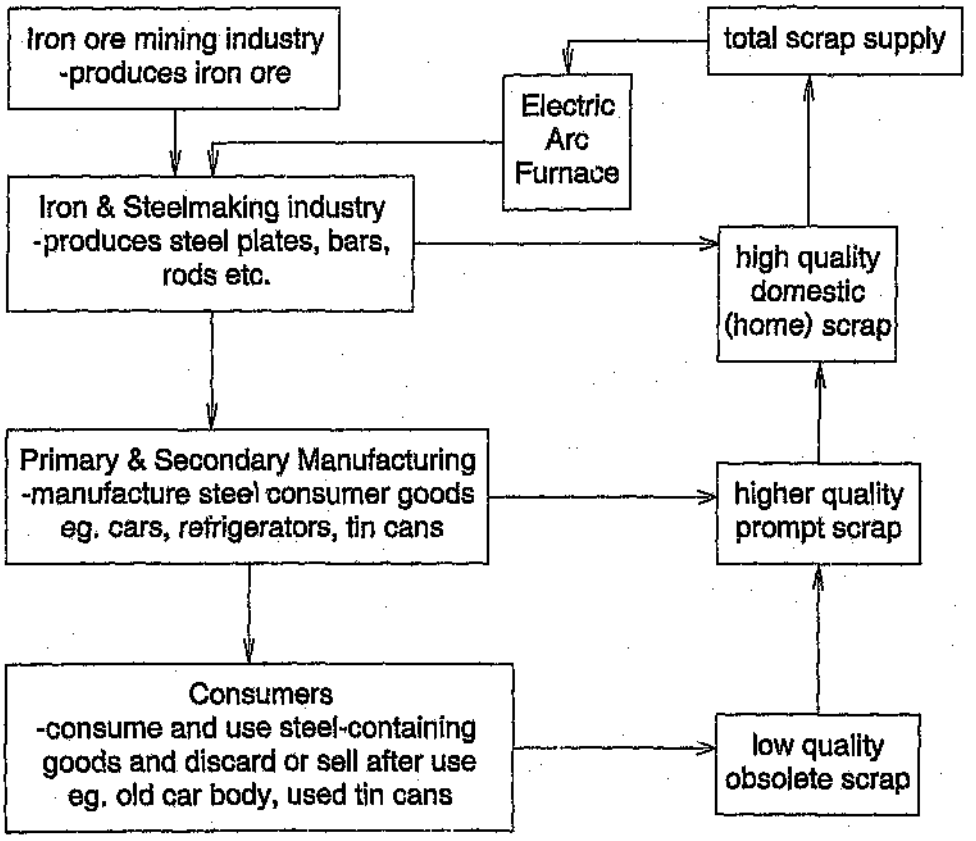
2.1 Defining different scrap types

"Scrap" cannot be "produced" or "manufactured" in the strict sense of the word, but can be defined as pieces of ferrous metal which occur:

- as a by-product in the **steelmaking process** (internal or domestic scrap/ reverts);
- or which is produced as a by-product in the **manufacture of steel-containing parts or goods** (prompt scrap);
- or which is **discarded** after use in the form of **consumer goods** (obsolete or capital scrap).

The following figure illustrates the creation of scrap.

Figure 2.1 How scrap is "created"



Morrison [66] remarks that a country's domestic scrap reservoir is a direct product of its level of industrialisation, while its consumption of scrap is closely correlated with its level of steel production.

In the past, the development of so-called "mini-mills" was strongly influenced by the expansion of the scrap market. Concurrent with the growth in the EAF steelmaking route, the **availability of scrap**, which is the primary feedstock for these furnaces, has fallen short of requirements (Barnett and Kopfle [7]).

The current situation is as follows:

- **internal scrap** (i.e. from iron and steel plants) is **decreasing** rapidly;
- **prompt scrap** (i.e. from the industry processing the steel products) is **not increasing** much, and appears to be more or less proportional to steel production;
- the only scrap source which is **increasing** is **obsolete or capital scrap**, (i.e. what is recovered from used or dismantled products.)

Table 2.1 Different steel scrap categories

Steel scrap categories	
Prompt Industrial Grades:	No. 1 Dealer Bundles No. 1 Factory Bundles Bushelings, clips Cut Structurals Turnings
Obsolete Grades:	No. 1 HMS RR Rails, Wheels Plate, Structural Shredded No. 2 HMS No. 2 Bundles

Internal (home) scrap, which has traditionally been used as high-quality scrap by steelmakers, has decreased in availability because of the improved continuous casting rate and rolling yield. In 1995, US scrap supplies consisted of 27 per cent home and 73 per cent purchased scrap. This represents a substantial shift from the 1960's when home scrap typically made up more than 60 per cent of the total supply (Morrison [65]). Since the later part of the 80's, when this continuous casting rate was established, the rate of scrap generation has been nearly unchanging. Most of the steel plants with 100 per cent continuous casting practices generate home scrap at a rate of 10 to 15 per cent of total metallic charge (compared to yields of 50 to 60 per cent in foundries).The relative unavailability of these high-quality scrap grades has forced steelmakers to use the lower quality grades including obsolete scrap which is increasing.

Prompt scrap, which is highly desirable to both integrated mills and mini-mills making higher-quality products because of its low residual content and consistent quality, is generated in the initial stages of finished steel consumption. This is the

most critical grade needed by EAF steelmakers entering the sheet and engineered long products markets.

The two highest-quality forms of prompt scrap are no.1 bundles and no. 1 bushelings. These two grades are most sought after by flat rolled steelmakers because of their low residual content.

The type of scrap which has the largest effect on scrap generation is **obsolete scrap**, the accumulation of which increases in direct proportion to the increase in world steel production. Obsolete scrap may now have reached 2,5 to 2,8 per cent of the total world steel accumulation, and can be expected to maintain this rate of increase in the future. World steel accumulation exceeded 6 billion tons in 1990, and will keep on increasing along with the increase in crude steel production in the future, and is expected to top 10 billion tons in the year 2000. The following table illustrates the typical lifetimes of various steel products before they are recycled.

Table 2.2 Typical steel-product lifetimes

Type of steel product	Typical life expectancy (years)	% of scrap supply *
Construction	25 - 100	30 - 50
Automobiles	8 - 15	15 - 20
Industrial machinery	7 - 15	15
Pipe & tubing	7 - 15	3 - 5
Ships & barges	20 - 35	1 - 5
Consumer prod. containers	1	4
Railroad equipment	25 - 35	4
Appliance/office furniture	7 - 15	2 - 3
Farm machinery	7 - 12	2
Construction & mining machines	7 - 12	2
Industr. & shipping containers	1 - 7	1
Electric transformer boxes	5 - 10	1
Non-durable consumer items	3 - 5	1

* Industrialised countries

Barnett and Kopfle [7] make the assumption that some 85 per cent of all steel consumed in a given year can eventually be recovered as obsolete scrap and then conclude that, although there is a tremendous potential supply of scrap world-wide, much of it cannot be economically recovered.

2.2 Problems with scrap supplies:

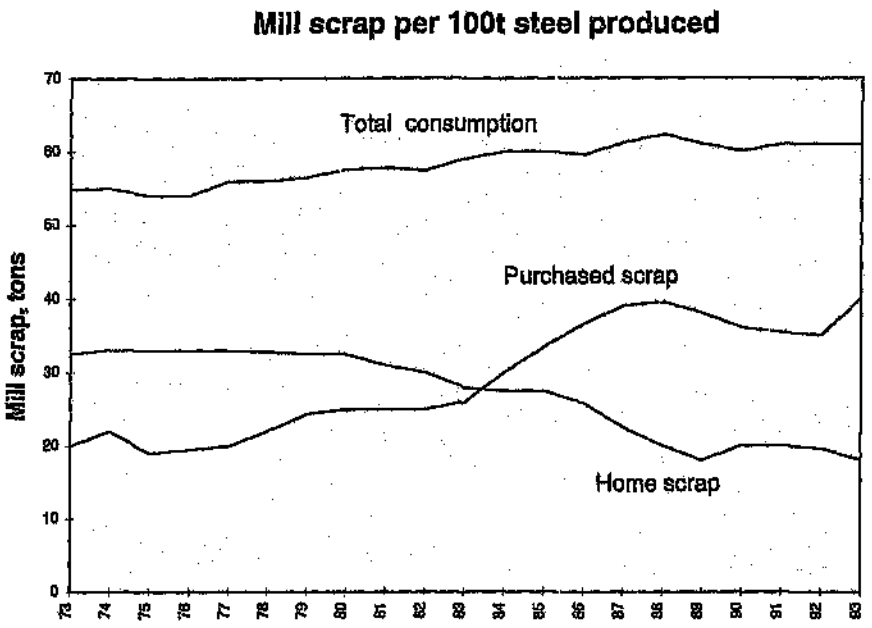
2.2.1 Availability

Obsolete scrap supplies are increasing and accumulating, and at a rate which is proportional to the increase in world steel production. Constant and increasing pressure is however being exerted on the scrap market. A lot of this is due to the increasing need for scrap by new mini-mills which are coming on stream.

The use of home scrap, or scrap "created" as a by-product of production, has traditionally been a good source of high quality feedstock with low impurities. Since continuous casting however, continues to become widespread, the amount of internally generated scrap is drastically being reduced, increasing the demand for purchased scrap. Also, new technologies allow electric arc furnace plants to produce higher quality products with longer lifetimes, which keeps them (the products) out of the scrap cycle for a longer period than before (Scarnati [87]).

Figure 2.2 shows the declining trend in home scrap compared to the increase in purchased scrap per 100 tons of steel produced.

Figure 2.2 Home scrap vs purchased scrap comparison



The crossing point of the two lines reflects the advent of continuous casting, thin slab casting and other new technologies which increased production efficiencies. Barnett and Kopfle [7] predict that by the year 2000, all the US and most other steel industries will be essentially 100 per cent continuous casting. They add that home scrap generation in the primary end falls from the traditional 18 per cent to only two percent due to continuous casting.

The above-mentioned factors are thus forcing scrap users to turn more to obsolete scrap as source of iron units. But the biggest problem with obsolete scrap is its quality.

2.2.2 Quality - the "residuals" problem

The tremendous growth in electric arc steelmaking has led to an unavoidable quicker turnabout of scrap and consequently, to increased contamination of scrap by

other elements. Steel produced from scrap contains other metals in its final form and when that product is scrapped, it is difficult or sometimes impossible to separate these metals which in turn contaminate the steel produced there-after. New steel applications have increased the number of additives to steel which must eventually be removed again during remelting.

A few **quality aspects** considered in evaluating the quality of scrap according to Chatterjee and Singh [17] are:

- The **absence of tramp elements** increases the quality of the scrap
- Purity, or the **absence of non-metallic substances** affects productivity and energy consumption.
- The **density and shape of metallics** is another quality factor which influences the number of backcharges, productivity, energy consumption and damage to furnace walls and refractories.
- Another beneficial aspect which improves the quality, but which is not present in scrap is the **energy content**, i.e.carbon content. This can be found in products such as DRI, HBI and iron carbide and reduces power consumption.

2.2.2.1 Chemical composition of scrap

Considering the fact that most of the scrap used is obsolete scrap, the chemical composition becomes an important aspect in determining its quality.

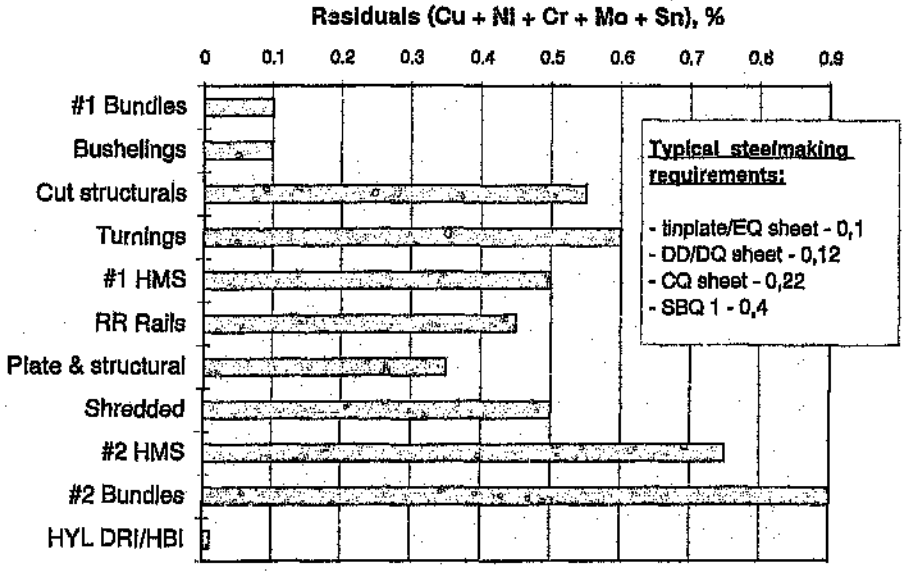
The residuals Cr, Ni, Mo, Cu, Sn, often ranging from 0,15 to 0,75 per cent depending on the type of scrap, have an adverse effect on the mechanical properties of the steel. That is why the use of EAF's (using scrap only) for the production of deep drawing quality steels, as well as low carbon steel products, is generally avoided. Also, the nitrogen content of EAF steels is higher then that of OH or BOF steels. As a result, steels produced in arc furnaces usually have poor ageing characteristics which make them practically unsuitable for deep drawing applications.

All of the scrap grades contain some level of contamination of residual elements that must be eliminated or diluted. Low residual scrap, such as prompt industrial scrap, can be used to achieve the needed dilution. The supply of prompt scrap, however, is limited since much of it is captive to companies which produce it which means that these companies use it themselves as scrap.

Figure 2.3 indicates typical residual contents for DRI together with various grades of steel scrap. Restrictions for different steel products are also indicated (Scarnati [87])

Figure 2.3

Typical residual content of scrap



TInplate/EQ - Electrolytic Quality, DD/DQ - Deep drawing Quality/Drawing Quality
CQ - Commercial Quality, SBQ1 - Special Quality Bar (Engineered Bar)

Only about half of the prompt industrial scrap generated is available to the steel industry as its only source of low residual scrap. The demand for low residual scrap has increased since the start-up of new thin slab casting operations which added further to the lack of availability - all of this, however, renewing interest in DRI. The use of DRI could soften the lack of low residual scrap and enable the use, in greater proportions, of lower grades of scrap, diluting their residuals by mixing them with DRI.

Although the ferrous industry is taking steps to improve the preparation and classification of purchased scrap, scrap processors cannot change the scrap chemistry. Regardless of the technique employed, they cannot metallurgically remove or lower the residual levels in the scrap. This is not the case with a manufactured product like DRI.

In the past, this problem of residual elements in scrap, was controlled by **selective purchase** and **blending** of charge mixes, but over the last two decades, the average residual level has tended to rise, thus creating an acute shortage of low residual scrap for electric steelmaking.

In Europe, North America and Japan, special efforts are being made to increase the scrap recovery and improve its quality by setting up **specialised scrap collection centres** and by **pre-treatment** of scrap involving shredding, copper elimination, detinning etc. It is claimed that this will enable scrap to be used in the production of thin gauge flat products. However, these efforts are still in the planning stage and no worthwhile impact has so far been reported by the industry of these techniques of scrap processing.

2.2.3 Price volatility

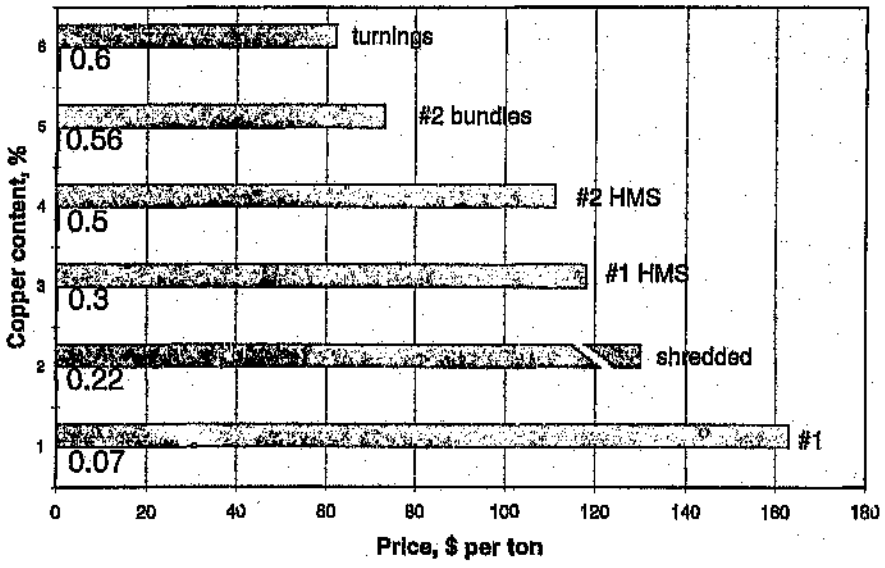
Obsolete scrap is basically elastic in price, discarding seasonal factors, and depends essentially on demand. Prices will go up or down in response to demand, within a reasonable price range

Low residual scrap supply, however, is not elastic. While demand continues to increase from new flat product mills, prices will rise. Scarnati [87] uses as an example, July 1994 bids on automotive factory bundles which increased by $21/t over previous levels, to over $151/t.

Figure 2.4 shows a general range of prices for different scrap grades as a function of quality (in this case the copper content).

Figure 2.4

Scrap prices as function of Cu content



2.2.3.1 Price mechanism of scrap

The price mechanism of scrap works well. During peak steel demand years, collection and processing of scrap that would otherwise be considered uneconomical

becomes feasible due to higher prices. Price increases for scrap will initially bring forth substantially increased supplies. The extra supplies may not be the best grades available, but in a seller's market the customer's ability to tolerate the grades offered tends to increase. As the scrap price rises, at some point it becomes more expensive to produce steel from scrap than from iron ore. The incentive to the integrated producer is then to cut back on purchases of scrap and increase the proportion of hot metal, if available.

The higher prices and lower availability of top grades of scrap continue to present difficulties for steelmakers, again forcing them to look at alternative iron units such as DRI. EAF operators thinking of entering the flat products market, as well as mills producing special bar quality (SBQ), wire rod, and seamless tube, are dependant on no.1 bundles and other prime scrap to meet product quality standards (Barnett and Kopfle [7]).

Many of the experts in the scrap industry agree that recent increases in steel scrap prices are indicative of the **re-establishment of a new and higher pricing level for scrap**, and not just the typical price cycles associated with this material. Morrison [65] is of the opinion that elevated prices are a reflection of structural changes that are taking place in supply as well as the demand side of the US scrap market, and that the effect that these factors will have on the scrap market, and specifically prices, will determine whether mini-mills will continue to enjoy an overall cost advantage over integrated works.

2.2.4 Scrap trade

The trade in scrap is the result of localised surpluses and shortages. An abundant domestic supply of scrap generally stimulates higher usage, but not necessarily to the extent that all supply is absorbed. Similarly, a scrap deficient area may curb usage but not necessarily so - some scrap deficient areas have developed into major scrap consumers and rely on imports to satisfy this demand.

Whether a country or region is in scrap deficit or surplus depends upon many factors including steel production process patterns, the stage of industrial development reached, historical levels of steel consumption, and whether the country or region is a net importer or exporter of steel products.

Several countries are both importers and exporters of scrap. The United Kingdom and the USA whilst having some imports, are prime exporters. A significant recent development is the growing net scrap import position of the Western European and Asia-Pacific regions. The CRU [22] reports that almost 90 per cent of all scrap imports involves only 13 countries; 6 in the EU, Turkey, and six in the Asia-Pacific region.

More than half of the world scrap trade is intra-regional due mainly to high transport costs but also, in regions as the European Community, to legislation governing the volume of scrap exported inter-regionally. Domestic consumers and governments of scrap producing countries often share the view that domestic scrap is an inherent property of such a country, exportable only when supplies are more than sufficient to satisfy the domestic demand.

2.3 EAF steelmakers' dilemma

Due to the various reasons outlined above, EAF steelmakers are experiencing increasing difficulties in obtaining good quality iron units as feedstock for their steelmaking operations. This state of affairs has forced steelmakers, iron ore producers and investors alike to consider anew, the use of directly reduced iron (DRI) as a substitute, if not alternative, to scrap in EAF steel production.

CHAPTER 3: DIRECT REDUCED IRON

3.1 Background and definitions

Direct reduction technologies have been developing since the early 19th century, as an attempt by steelmakers to produce iron directly from iron ore, avoiding high temperatures needed to melt iron ore. Besides technical problems, direct reduction technologies met with economical and financial difficulties in their development due to their relative unimportance in the shadow of ferrous scrap as a feedstock for EAF's.

More recently, the search for better quality iron units in the production of steel in mini-mills, as well as problems with price volatility of scrap has led to a renewed interest in the development of **direct reduced iron (DRI),** also called **sponge iron,** a source of metallics which contains no tramp elements and has a free iron content of about 90 to 95 per cent.

"Reduced Iron" derives its name from the chemical change that iron ore undergoes when it is heated in a furnace at high temperatures in the presence of hydrocarbon-rich gasses. **"Direct reduction"** refers to processes which reduce iron oxides to metallic iron below the melting point of iron. The product of such solid state processes are called **direct reduced iron (DRI),** whereas the product of the blast furnace is referred to as **hot metal** in the molten state, or **pig iron** in the solidified form.

The product can be fed to electric arc furnaces or oxygen converters or even, to any other iron and steelmaking plant in much the same way as ferrous scrap. In the oxygen furnace, DRI acts as a "coolant", while in the blast furnace it is used as charge material to increase productivity and decrease coke consumption (Bonomo [11]).

DRI can be produced either in lump, pellet or fines as a porous product which retains the original size and shape of the pellet and lump feed. DRI possesses the inherent tendency to "ignite" or spontaneously combust when wetted, causing problems in shipping, handling and storage when produced for merchant sales (Bandopadhyay and Ganguly [6]).

Hot briquetted iron (HBI) is DRI which has been mechanically compressed after reduction and before cooling into dense, pillow shaped briquettes, produced in most gas based units. HBI, which is the preferred form for the merchant product, has a lower porosity than DRI, adding more ease to shipping and storage, and reducing the danger of spontaneous combustion of wetted DRI. This additional production step, however, adds significantly to the production cost.

Iron Carbide or Fe_3C is a stable, finely granular material produced from high grade fine ores with around 6% carbon (McManus [58]). The carbon is added by reducing gases during reduction, binding with the Fe as Fe_3C. Generally, iron carbide is grouped among other reduced iron products, but technically it is distinct from

DRI/HBI because it has very little free metallic iron content, being a stable compound of iron and carbon.

A group of newer processes, called **direct smelting processes**, reduce iron oxide to metallic iron in a molten state directly from iron oxide to give a similar product to that of the blast furnace. These include the Corex process, Hismelt process, Itmk3, AIAI Direct Steelmaking Program (Weston and Thompson [100]), the Japanese Dios project (Furukawa [32]), and the Russian Romelt process (Romenets [81]).

The next table compares various characteristics of different kinds of reduced products.

Table 3.1 Product Quality Comparison

Components	Blast furnace iron	DRI/HBI	Iron Carbide
Metallic iron	95%	80-88%	1-2%
Iron as iron carbide	0%	0%	100%
Iron oxide (FeO)	0%	5-12%	1-2%
Carbon	4%	1-2%	6-8%
Gangue	1%	3-8%	1-3%

3.2 The Process

In direct reduction processes, the object is to **drive off the oxygen** contained in iron ore in various forms (sized ore, concentrates, pellets, mill scale, furnace dust etc.) in a solid state, to convert the ore **without melting to metallic iron.** From about 955°C lumps of oxide are reduced by carbon, at first retaining their shape, but starting to sinter and soften at about 1010°C and, depending on size, completing reduction. At about 1205°C they become a pasty mass which retains some of the original porosity. Soon afterwards DRI begins to absorb carbon, if it is available.

This is different from blast furnace practice, where the ore is taken to a liquid state and refined by removing the silica-rich slag layer. Because it is not refined, the quality of reduced iron is not as desirable as blast furnace pig iron. The remaining oxygen and silica contained in reduced iron must be removed in the steel furnace, at some added cost.

3.3 Required characteristics of raw material

Cunningham and Stephenson [23] describe the properties of raw materials as dictated by the different types of processes.

3.3.1 Vertical shaft process

Efficient reduction in a moving or fixed bed is encouraged by a **highly permeable bed,** promoting good gas to solid contact. Factors affecting the permeability of the bed , such as **size distribution** of the material, **ability to resist degradation** due to impact and abrasion, and the **physical and chemical behaviour** of the feed during reduction at elevated temperatures should be taken into consideration in

determining the suitability of a feed material for use in a vertical-shaft direct reduction process (Houseman [43]).

Feed materials having a relatively **narrow size distribution** are desirable for good bed permeability. Materials containing a high amount of fines are unsatisfactory because fines promote channelling of the gas flow and result in high dust losses, poor fuel economy and variability in the degree of reduction. Materials that show a sticking or clustering tendency during reduction also cause channelling. In moving-bed shaft furnaces they will prevent smooth descent of the charge, and with fixed-bed units they will make it difficult to discharge the product. Materials that swell, degrade or are weak in a reduced state also have a negative effect on bed permeability.

3.3.2 Rotary-kiln process

In this kind of process, **size distribution of feed material is less critical** than in the previous type because the heat and mass transfer in a rotary kiln are not greatly influenced by the permeability of the bed. Iron ore fines as low as minus 3,4 mm, which would not be suitable in a vertical shaft furnace, can be used successfully in a rotary-kiln system (Houseman [43]).

Feed materials with **good cold strength** are desirable, seeing that materials that degrade during heating or reduction generate fines that leave the kiln as unreduced dust and would require special handling. Materials displaying sticking or clustering phenomena negatively influence the kiln operation by forming ring-type build-ups along the wall of the kiln.

3.3.3 Fluidised-bed process

The fluidised-bed process necessitates **consistency between the size distribution** of the feed and the attainment of good fluidisation characteristics. A high portion of relatively coarse particles in the feed could lead to the segregation of this coarse fraction at the bottom of the bed. A too high percentage of fines, however, will necessitate the use of internal cyclones to minimise dust losses, which could also lead to the formation of deposits in the reactor.

Materials with a narrow size distribution show a greater tendency to cause 'slugging' of the bed, which decreases the efficiency of gas-solid contact in the reactor. Ultimately, the optimum size distribution will be specific to the particular operating conditions of the fluidised-bed system. Some ore fines cause problems in a fluidised-bed system due to their inherent sticking or agglomerating behaviour.

3.4 Physical properties of DRI

The physical strength of the DRI product is substantially lower than the feed material. Breakdown of the product can however be minimised by locating the DRI plant close to the steel making facility, or to use a good quality feed material. DRI material can also be **agglomerated or briquetted**, in the case where the product is intended to be shipped over long distances or submitted to considerable handling.

Briquetting also increases the density which reduces the chances of DRI getting trapped in the slag and becoming oxidised.

3.5 Chemical composition of DRI

Most of the impurities and gangue of the feed material end up in the DRI product. Cunningham and Stephenson [23] give an outline of some of the most important elements and their effect on reduction :

- **Iron** - to optimise operating cost, the iron content of a feed material should generally be as high as possible - 66 to 69 per cent.
- **Silica** - a high SiO_2 content results in high slag volumes in the steelmaking process and requires additional power consumption. On the other hand, a very low silica content could result in decrepitation, excessive swelling, and sticking during reduction causing production inefficiencies. DRI with too low a silica content could also lead to degradation during handling and shipping.
- **Alumina** - Al_2O_3 content does not seem to have a large effect on the reduction process, but seeing that it is an acid gangue, additional flux would be needed in the steelmaking process, resulting in a higher slag volume.
- **Lime** - CaO in the raw material usually makes a positive contribution to the product in both the direct-reduction and steelmaking process. In the steelmaking process especially, contained CaO acts as a fluxing agent, decreasing the requirements for added flux.
- **Magnesia** - MgO in the feed material increases reducibility, decreases low-temperature breakdown and improves the strength of the DRI product.
- **Alkali** - the presence of alkali oxides in the feedstock promote swelling and degradation during reduction, and could lead to problems with bed permeability or dust losses.
- **Phosphorus** - the presence of phosphorus in the raw material does not affect the reduction process. In some electric furnaces this element mostly remains in the slag, so that very little ends up in the metal.
- **Sulfur** - the sulfur content of feed material is a major concern in the reduction process that could lead to catalyst poisoning if the off-gas is recycled to a reformer. It also contributes to environmental problems in steelmaking.

3.6 Physical characteristics of DRI in comparison with scrap:

- **Constant and small sized pellets or briquettes**, making it suitable for **mechanical handling** and **continuous feeding** using some sort of mechanical feeder, working with arc power on, rather than charging scrap via the roof, or in old furnaces, via door pans, with power off.
- **Known and constant analysis, with little or no contamination by tramp elements**, this desirably lowers the tramp elements analysis of the steel,
- Some content of **residual non-metallic impurities**, usually less than dirt in low quality scrap such as No. 2 Bundles, but more than in better scrap qualities; this requires some flux for slagging off and power to form the slag.
- Some **residual oxygen content** from unreduced iron oxides.
- Cunningham and Stephenson [23] mention that the use of DRI in the arc furnace is a **function of its economics**. Up to 70 per cent of total scrap was replaced by continuously fed direct reduced pellets, but beyond about 40 per cent if was

found that disadvantages begin to arise i.e. there is an increasing demand for fluxes needed to slag off the impurities and a higher usage of electric energy because of the necessity to form this additional slag and also to reduce oxygen (about 10 to 20 kW/ 1% oxide).

- Another problem is **increased refractory consumption.** If large amounts of pre-reduced pellets are used instead of scrap, the arcs are struck between the piled pellets and the electrodes, thus little shielding of the arc by scrap is available, especially as it appears that the power factor using pellets is higher than that normally obtained in scrap practice, thus lengthening the arc.

3.6.1 Use in the EAF

DRI lump, pellets or briquettes can be dumped cold into a steelmaking furnace along with scrap, using standard bucket charges. In the electric furnace, DRI works best if it is charged after a hot liquid bath has been made by melting scrap. DRI requires more heat input than scrap, so there is an added cost from using DRI in an EAF. DRI technology suppliers advocate hot charging DRI where possible, to offset added power costs for melting, but this is only possible where and when DRI plants are situated near the point of consumption. The carbon content of DRI also off-sets higher power requirements.

3.7 Other advantages

3.7.1 Lower cost

An advantage and attraction of direct reduction, coupled with electric arc furnaces, is the lower capital cost and lack of reliance on coke as a fuel source. More stringent air quality parameters are making coke more costly and causing some older coke batteries to close. Houseman [43] mentions that experience shows that a DR-EAF facility can be constructed in less than two years, as compared with 5 to 7 years for a blast furnace/BOF facility. Brown [15] also notes that several DR plants have been constructed in less than 18 months and have reached design rating within 30 days after start up.

3.7.2 Availability

With the exception of one captive plant in the USA and one in Canada, all gas-based DRI plants are located in developing countries. Of nearly 24 million tons of DRI produced in 1993, only about 5 million tons where commercially available. Of that amount, barely 2 million tons entered the US market. In contrast, the demand for DRI in the US has been calculated at from 6 to 7 million tons in 1995 and is expected to increase to approximately 10 million tons when new steel mill projects in North America are taken into account. As a replacement for low residual scrap, the situation with respect to DRI appears to be high demand and low supply. But, unlike low residual scrap, the supply can be increased.

3.7.3 Quality

Unlike scrap, DRI quality is uniform and predictable. Since it is a virgin iron source, it is virtually free from tramp elements and residuals. The chemical composition is

knowr from the start, thus allowing the use of DRI as a dilutant when mixed with different grades of scrap to lower their overall residuals content.

'e physical characteristics of DRI and HBI, such as shape and density, are uniform. These factors are important since t. ey allow DRI to be continuously charged. Bucket charging of HBI is more predictable than scrap charges, allowing the elimination of back-charges due to density variations which occur with scrap.

3.7.4 Associated carbon

DRI has another added benefit when compared to scrap in that it has an associated energy value in the form of **combined carbon** which increases furnace efficiency. High carbon DRI, when used with oxygen practices, can have a noticeable impact on reducing the power consumption and increasing the output of the electric arc furnaces.

3.7.5 Direct charging

A further development, the use of hot DRI directly transported and charged to a furnace, can **reduce energy consumption** by as much as 16 to 20 per cent by making use of the energy value of the DRI at temperatures greater than 600°C. This is only available when combining a DRI plant with an EAF meltshop (i.e. Saldanha Steel).

3.7.6 Price

Unlike scrap prices, which are routinely published by grade and market, **prices of DRI and HBI** are, basically, **open to negotiation** with the producer after taking into account the basic production cost and profit, and adding in the variations in the market such as supply and demand, spot or contract purchases, etc. Generally, DRI prices have been in the range of **$109 to $136 per ton** over the past decade, and DRI and HBI will typically be at a price equivalent to, or slightly higher that of premium low residual scrap grades (no.1HMS +,=$15/t).

Since price is determined by the price and availability of basic raw materials (iron ore and natural gas) plus labour, operating and investment expense, and the return on investment, it has generally been held that plants in developing countries are more attractive than US based plants since these aspects, especially labour and investment, tend to be lower. Thus, the cost of shipping becomes an important item in the total cost of DRI or HBI delivered to the mill (Scarnati [8,7]). Cost of shipping per Fe-unit, however, is lower for DRI/HBI than for iron ore. Hence the tendency to construct DRI plants close to sources of ore, especially in cases where gas is also available - i.e. Venezuela.

3.7.7 Blending of DRI with scrap

Considering the increasing pressure on the low residual scrap market, steelmakers who must meet strict product limitations should develop a **blend of iron units** that would provide the best quality charge at the **lowest possible cost per ton** of iron.

This can be done by mixing low residual scrap, cheaper low quality scrap grades and sufficient DRI or HBI to dilute the residuals to the required levels.

The per ton cost for **blends of different percentages** of DRI, No.1 Bundles and No.1 Heavy Melting Scrap could be lower if mixed to reach a pre-set level of residuals. By replacing No.1 Heavy Melting Scrap with the much lower priced No.2 Bundles to reach the same residuals content

Once DRI drops below 40 per cent of the charge, much higher levels of premium scrap are needed to help offset the very high residuals in the No. 2 Bundles. The objective is that more lower prices scrap can be used by taking advantage of the high purity of DRI, while getting the added benefits of additional carbon.

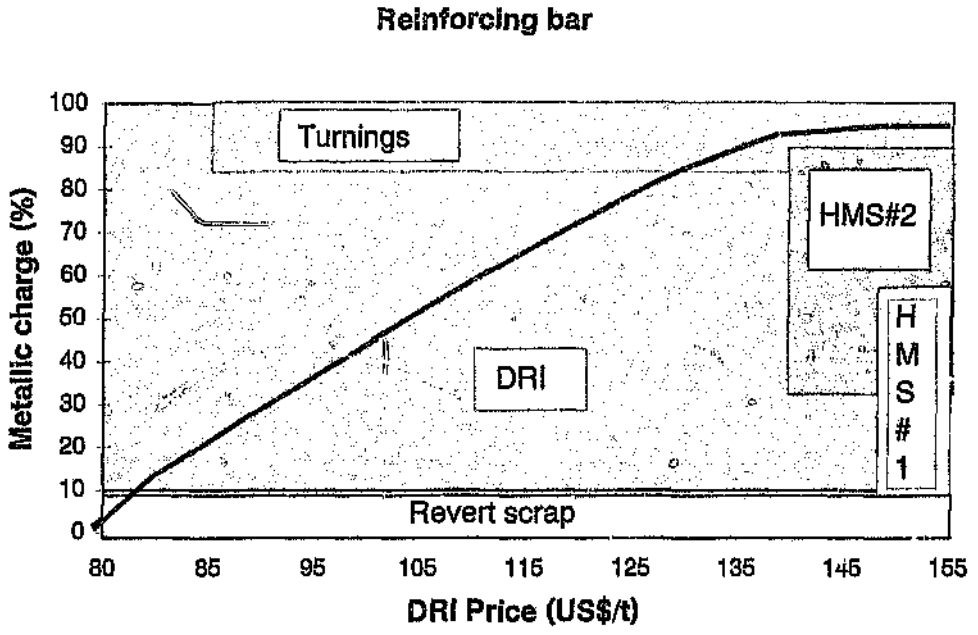
CRU [22] forecasts that the proportion of DRI/HBI used in EAF is set to change in the future. Specifications for flat products and quality long products dictate the use of 40 to 70 per cent low residual metallics in the furnace. In North America, however, electric steelmakers are planning to use DRI for 20 to 30 per cent of the charge, with low residual scrap and pig iron making up the remainder.

The value of a metallic commodity such as DRI is defined by the quality of the steel to be produced. If DRI is used for rebar production, with a high tolerance for residuals, its value is that of the displaced scrap. If used for higher quality steel grades, its value is determined by the opportunity to produce high steel grades (Quintero [77]).

This can be illustrated as follows in figure 3:

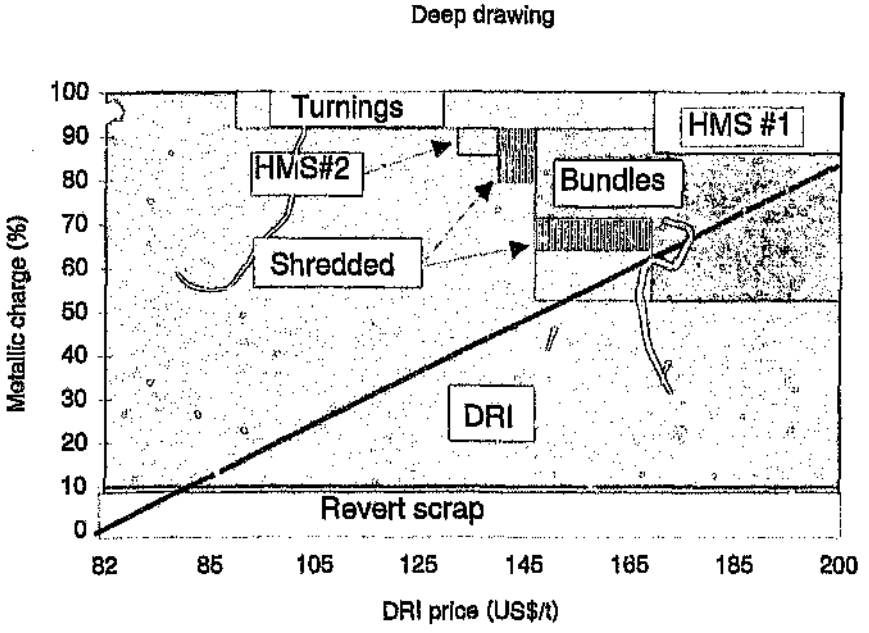
Figure 3.1 represents the metallic charge mixing options for various DRI prices. In the case of **rebar**, the residual content limitations are less strict, but need to be taken into account. Quintero [77] explains that for a DRI price of less than $90/t, the charge which optimises the liquid steel cost is 90 per cent DRI and 10 per cent revert scrap. For a DRI price of more than $90/t, liquid steel cost can be optimised by charging other types of scrap such as, first, turnings, if DRI prices increase,then #2 HMS, and then #1 HMS. If the price goes beyond $150/t, no more DRI is used, and the price then represents the value of DRI since it is the maximum price that a rebar meltshop would be prepared to pay for it. The DRI price is therefore equivalent to the #1 HMS price, although more lately, it commands a premium.

Figure 3.1 Metallic charge mixing options - reinforcing bar



For deep drawing quality steels (DDQ) however, the DRI is needed to satisfy the limits of the residuals level (figure 3.2).

Figure 3.2 Metallic charge mixing options - deep drawing steel



Some scrap substitution takes place as DRI price increases, but only within the range which will allow satisfying the quality restrictions. The value of the DRI is thus located between the more expensive charge up to what the product margin for that steel grade allows since it is not possible to produce this steel grade with 100 per cent scrap alone. The value in this case is not determined by the cost of the scrap substitution, but rather by the opportunity of being able to produce the required product (Quintero [77]).

The ability to blend scrap substitute products with scrap allows the steelmaker to vary the grades of scrap used, in most cases reducing the overall metallics cost by permitting the use of lower grades of scrap otherwise not considered for an all scrap charge. However, since many of the companies that operate DRI plants are in developing nations which use their captive production in their own steel mills as scrap replacement, the general impression of DRI vs scrap has been an either/or proposition. Furthermore, the cost of producing DRI depends on the price of natural gas, iron ore and other aspects which, historically, have been higher in the USA than in the developing countries. US mills have tended to regard DRI as a good product which is too expensive to consider, as long as there is plenty of scrap available at lower prices.

3.7.8 Environment

Environmental issues are of importance and becoming more so. The use of DRI and HBI avoids the problems of hazardous contaminants such as lead or cadmium in EAF dusts.

3.8 Disadvantages

3.8.1 Reoxidation and auto-ignition

DRI also has a distinct disadvantage compared with scrap. Due to the nature and surface area of untreated DRI, it has been found to be highly reactive with moisture. Being a non-equilibrium and porous product, it has an **inherent tendency to reoxidise** in a self-sustaining manner, a strongly exothermic reaction, if the temperature in a pile goes beyond a certain limit. The heat generated, coupled with the poor thermal conductivity, can lead to auto-ignition of DRI. Considerable research into various **methods of passivation** has been done, and the problem has been largely overcome. One of the more effective passivation methods is **hot briquetting**, where DRI is briquetted at more than 650°C to densities greater than 5g/ml. Transportation and storage of DRI in the form of HBI, are relatively easier because of its high density and low reactivity - this has made briquetting plants a part of the mainstream in gas based units.

3.8.1.1 Safety precautions

The International Maritime Organisation (IMO) has laid down a code of safety practices serving as a guideline to the insurers of DRI cargoes. Depending upon the physical type, the cargo may have to be stored in an inert atmosphere or at least one adequately ventilated, and contact with moisture should be minimised. Some degradation of the product still occurs during storage and transport. On a typical

ocean voyage, metallisation may drop by 1 to 2 per cent, and there will be some loss to fines because of abrasion encountered during handling.

3.8.2 Residual gangue

As reduced iron **contains some gangue** and the increase in the percentage of reduced iron added causes an increase in the power consumption, there are some mills which restrict the mixing volume. However, it is foreseen that the production of reduced iron will increase to satisfy the purpose of stabilising the supply of iron sources as well as in response to the present, the majority of reduced iron is consumed in the producing regions and only 13 per cent (2 million tons) of the total production is exported. But the export of HBI, which is easy to transport, is expected to increase in the future.

3.9 The choice of substitution between scrap and DRI

Situations where a part of scrap could be substituted with DRI:

- The first situation is when **good-quality scrap runs short** so that the **quality of steel products deteriorates**, and it is necessary to add reduced iron to raise the quality of the raw material. DRI should, however, be considered as a complement to scrap, rather than as a substitute. Proper use of DRI can improve the quality of lower grades of scrap so that they can become metallurgically equivalent to premium scrap and at lower overall prices.
- The second situation is in mini-mills built in **regions where the delivery of iron sources** such as scrap is **difficult** or where the **construction of an integrated steelworks** with BF is **not particularly necessary** from the viewpoint of the size of the demand, in which case reduced iron can be used as the main raw material.
- The development of DRI processes were initially thought suitable for scrap-poor developing countries building up their steel industries and for those countries which had inadequate supplies of ferrous scrap, either in quantity or quality, to feed their electric arc furnaces.

There has been a distinct dichotomy in the utilisation of DR plants between the developing and industrialised countries. The **gas-based** processes, which operate with varying degrees of success in Latin America, the Middle East and South East Asia have, with minor exceptions, ceased operating in the industrialised countries of the Western World. The major reasons for the poor performance of gas-based DRI plants in industrialised countries were the traditionally low price of scrap compared to DRI, and the costs of natural gas and electricity. In the developing countries, at least those with ample supplies of natural gas, the situation was, however, radically different.

The **coal-based** systems have generally not followed the same pattern of development as the gas-based ones. Having appeared on the scene later than the gas-based processes, their development was retarded by technical problems.

3.10 Trade in DRI

Most of the global DRI production is found within integrated plants and the product is consumed in the electric arc furnaces on site. There is, however, a significant trade in DRI, either from merchant plants built specifically for this purpose or from integrated plants with excess DRI capacity. When the steel industry is in stagnation and supplies of ferrous scrap are more readily available, then the merchant plants are much more likely to operate at a low capacity utilisation than the integrated plants. Merchant DRI, therefore, is a direct competitor to scrap, whereas DRI produced in an integrated plant is only indirectly affected by scrap supplies and processes.

The 20m tpy of new capacity currently under construction includes about 45 per cent (9,3 mty) of merchant capacity, of which nearly 66 per cent (5,9 mty) are mostly owned by three iron ore mining companies: **BHP, Cleveland Cliffs and Lebendinsky (Russian).** The other 3,3 mty of planned merchant capacity is owned by steel mills as a surplus to their internal requirements. In a few cases modules are built essentially for supplying the merchant market.

CHAPTER 4: DRI TECHNOLOGIES

4.1 Background

The **Direct Reduction (DR) process** has been known for many years and a commercial plant was operating as long ago as 1957. The process was initially slow to gain acceptance, but began to take off in the 1970's as installed capacity increased rapidly. In the development of direct reduction to the position of importance that it holds in the steel industry today, more than a hundred different DR processes have been operated on an experimental basis. Many were found to be economically unfavourable or technically unsatisfactory and had to be abandoned. However, some met with success and have been subsequently improved and developed satisfactorily into full scale commercial operations. In some instances the best features from several different processes have been combined to develop newer and better processes.

Some processes where designed for use with particular raw materials or fuels that are no longer economically available and consequently they where discontinued in spite of the fact that they where technically sound and relatively efficient at an earlier stage. On the other hand, some DR processes that may not have been economic in some circumstances are now in operation because they are the best suited for the raw materials and fuels indigenous to the region in which they are located.

The two main distinguishing technologies are gas-based and coal-based.

4.2 Gas-based DR technologies

This category uses primarily **natural gas** (methane, CH_4), which is "cracked" or "reformed" into a mixture of reducing gases (carbon monoxide and hydrogen) using carbon dioxide (CO_2) or steam (H_2O). Other gasses that can be used include **purified coke oven gas, synthetic coal gas, naphtha and liquefied natural gas (LNG).** The reforming process takes place in a reformer, and the heated gas from the reformer is passed through the iron ore in the furnace where it reacts with the oxygen in the iron and reduces (removes the oxygen from) the iron oxides to produce free iron. Some of the free iron is carburised into iron carbide in processes that use carbon containing reductants.

4.2.1 Reactor vessels for gas-based reduction

Gas-based DR technologies can be further subdivided according to the type of reactor vessel into **vertical shaft furnace** types and **fluid-bed** technologies.

4.2.1.1 Vertical shaft furnace

Two gas-based processes comprise some 90 per cent of world DRI production and utilise the **Midrex and HYL vertical shaft furnace technologies**. Both Midrex and Hyl processes use direct reduction grade iron ore pellets and lump fed into the top of the furnace, which move down the shaft by gravity as the reducing gas flows up vertically. Differences in the two are primarily in temperature and pressure conditions of operation, and the type of gas reformer used.

The Midrex shaft operates at 800°C to 885°C, two atmosphere pressure, and uses CO_2 reforming. HYL operates at 925°C, six atmospheres pressure, and uses steam reforming to make process gas mainly composed of hydrogen and CO. Design capacity for Midrex units are now up to 1,2 mtpy while HYL is up to 750 000 tons per year.

Table 4.1 - Natural gas-based Direct Reduction Processes

Process	% world nominal capacity	Feedstock	Reaction vessel *	Temp. (°C)	Pressure (atm.)	Product
Commercial						
Midrex	50.3	lump/pellets	SF	860	2	DRI/HBI
HYL III	18.6	lump/pellets	SF	930	6	DRI/HBI
HYL I	13.5	lump/pellets	FBR	+980		DRI/HBI
AREX/Midrex	4.3	lump/pellets	SF	830	2	DRI/HBI
Ghaem	1.6	lump/pellets	SF	900	2	DRI
FIOR	1.1	fines	FB	700	12	HBI
Purofer	0.9	lump/pellets	SF	975		DRI/HBI
Iron Carbide	0.8	fines	FB	600	4	Iron Carbide
Developmental						
Circored		pellets	FB	<650	4	DRI/HBI
FINMET		fines	FB	600-800	10	HBI
SPIREX		fines	FB	800-850		DRI/HBI

SF - shaft furnace
FBR - fixed bed retorts
RK - rotary kiln
FB - fluidized bed
RH - rotary hearth

4.2.1.2 Fluid-bed technologies

There are three fluid-bed technologies for the reduction of iron ore: **FIOR** and its improvement known as **Finmet, Iron Carbide,** and **Circored.** FIOR is commercial, Iron Carbide is being commercialised and Circored is developmental.

In the **FIOR** fluid-bed ore reduction process, used in Venezuela, iron ore fines are the feed material which are suspended in a bed by upward flowing gasses. FIOR resembles a series of interconnected pressure cookers, operating at temperatures between 550°C and 790°C and pressurised to about 12 atmospheres. Design capacity of the only FIOR plant in operation is 440 000 tons per year.

The **Iron Carbide** process uses a single reactor vessel, in Nucor's case, with interior baffles that direct the iron ore particle flow along a maze-like path. Gas temperatures are near 600°C, with pressures near four atmospheres. Natural gas is reformed to

make a five-phased gas system comprised of H_2,CH_4,CO_2,CO_3 and H_2O. Nucor's design production rate is 320 000 tons per year.

Circored is a developmental gas-based fluid bed reduction technology of Lurgi Corporation. It uses two reactors in series to convert iron ore fines to metallic iron using steam reformed natural gas.

4.2.2 Fuels for gas-based reduction

There is a broad range of fuels which could be used to produce gaseous reductants for direct reduction processes. Natural gas is currently by far the most widely used of these, having the advantage of a low sulphur content, good transportability and easy convertibility to hydrogen and carbon monoxide by catalytic reforming with steam (Cunningham et al [23]).

In addition to natural gas, light hydrocarbons, such as butane or naphtha, can be catalytically reformed with steam to produce hydrogen and carbon monoxide. Other fuels which can be used are coke-oven gas and refinery tail gas which contain varying amounts of methane, and may be reformed in the same manner as natural gas to produce hydrogen and carbon monoxide.

4.2.2.1 Catalytic reforming

There are basically two methods of producing reducing gas from gaseous or liquid hydrocarbon feeds: partial oxidation and catalytic steam reforming. Cunningham et al [23] explain that although partial oxidation was developed earlier, reforming has developed to the point where its installations outrank partial oxidation installations in number as well as capacity.

Steam reforming is a catalytic process using a nickel-supported catalyst on a refractory base, such as alumina.

The following primary chemical reactions are involved:

Reforming

$$\Rightarrow \quad CH_4 + H_2O \Leftrightarrow 3H_2 + CO$$
$$CH_4 + CO_2 \Leftrightarrow 2H_2 + 2CO$$

Water-Gas Shift

$$\Rightarrow \quad CO + H_2O \Leftrightarrow H_2 + CO_2$$

For the production of reducing gas, high pressure is not essential because most DR processes operate at pressures below 10,2 kg/cm^2. Also, because a high content of hydrogen plus carbon monoxide is desired, the normal hydrogen-production steps of shift conversion and carbon dioxide removal are not required.

Factors favouring high-potency reducing gas are high temperature, low pressure, and low ratios of steam to carbon. The high temperature and low pressure result in

high conversion of hydrocarbon, and low ratios of steam to carbon maximise conversion of hydrogen and carbon monoxide.

When operating at low ratios of steam to carbon, care must betaken to avoid deposition of carbon on the catalyst. Carbon deposition decreases catalyst efficiency, causes catalyst breakage and concomitant bed plugging, and results in premature breakthrough of CH_4 and decreased lifetime. Carbon formation takes place according to the following reactions:

Methane decomposition:

$$\Rightarrow \quad CH_4 \Leftrightarrow C + 2H_2$$

Boudouard reaction or CO disproportionation:

$$\Rightarrow \quad 2CO \Leftrightarrow C + CO_2$$

Removal of the deposited carbon is accomplished through the following reaction:

Carbon steaming:

$$\Rightarrow \quad C + H_2O \Leftrightarrow CO + H_2$$

To produce a suitable reducing gas, a catalyst must be used that can avoid the deposition of carbon under low ratios of steam to carbon or a portion of the feedstock must be reformed under high ratios of steam to carbon, and then a high enough 'mixed' temperature to avoid the carbon-deposition temperature range during the completion of the reforming.

Catalysts fortunately now exist that are strong enough to permit operation at the high temperatures (925° to 980°C) required to produce good reducing gas. Most reforming catalysts are highly susceptible to sulfur poisoning and hydrocarbons to be reformed should thus be desulfurised to 1 ppm or less (CRU [22]).

4.3 Coal-based DR technologies

Several coal-based technologies are in commercial production today, but their growth has been limited by a generally poorer quality product due to ash and sulphur contamination from coal, and they have tonnage capacity limitations compared to gas-based technologies (Cunningham et al [23]). However, for certain local conditions, a lower quality product may be acceptable. Currently operating coal-based reduced iron products would not be expected to survive as merchant products in the international market.

Operating coal-based technologies are dominated by the **rotating cylindrical kiln types** such as **SL/RN, DRC, ACCAR and Codir,** in which coal is charged directly with lump iron or pellets, operating at about 900°C, and at atmospheric pressure. Most of these plants have design capacities limited to under 350 000 tons per year.

4.3.1 Rotary hearth furnace

Rotary hearth furnace technology is exemplified by **INMETCO** and by Midrex's FASTMET process, in which coal is pulverised and blended with iron ore into a pellet

that is placed onto a hearth in a shallow layer only one or two pellets deep. INMETCO and FASTMET operate at 1250°C to 1350°C and atmospheric pressure.

The only INMETCO plant has a capacity of 25 000 tons per day and is used for steel waste oxide recycling. INMETCO plans to market the technology to a larger scaled-up version for iron ore reduction, and has licensed its technology to Mannesman Demag. Midrex's FASTMET technology is being piloted in Kakogawa, Japan, by Kobe Steel, which is Midrex's parent company, and is expected to have a design capacity of about 450 000 tons per year, when made commercial (Nurse[70]).

Table 4.2 Coal-based Direct Reduction Processes

Process	% world nominal capacity	Feedstock	Reaction vessel *	Temp. (°C)	Pressure (atm.)	Product
Commercial						
SL/RN	3.8	lump/pellets	RK	1000	1	DRI/HBI
Jindal	1.6	lump/pellets	RK		1	DRI
Codir	1.4	lump/pellets	RK	950-1050	1	DRI
OSIL	0.7	lump/pellets	RK		1	DRI
SIIL	0.6	lump/pellets	RK	1000	1	DRI
DRC	0.5	lump/pellets	RK	1075	1	DRI/HBI
Tisco	0.3	lump/pellets	RK		1	DRI
DAV	0.1	lump/pellets	RK		1	DRI
Kinglor-Metor	0.1	lump/pellets	SF	1050-1100	1	DRI
Developmental						
Circofer		pellets	FB	950		DRI/HBI
FASTMET		pellets	RH	1250	1	DRI
INMETCO		pellets	RH	1100-1200	1	DRI

SF- shaft furnace
RK - rotary kiln
FB - fluidized bed
RH - rotary hearth

4.4 Gas-based vs. coal-based

Although many direct reduction process technologies have been tried in the last thirty years, the **Midrex** and **HyL** processes, which use reformed natural gas as a reducing agent, have evolved beyond the others and hold the major share of the market. Together, these technologies accounted for 90 per cent of the estimated 33 mt of global DRI production in 1996, excluding hot metal and pig iron production.

Due to a considerable amount of research on the development of coal-based technologies which accept iron ore fines, these are starting to pay off. Although the coal-based processes have proved to be more difficult to get off the ground

compared to those based on gas, efforts persisted to be made due to the wider availability of coal than natural gas.

The coal-based **SL/RN process** was developed at around the same period that the Midrex and HYL processes where getting off the ground, but whereas the gas-based processes where operational in the early and mid-70's, the coal-based process only started operating in the 80's. India hosts more than 50 per cent of the SL/RN plants, and has shown considerable interest in the coal-based technologies. One of the inherent limitations of existing coal-based plants is their relatively small unit size compared to the gas-based technologies.

Table 4.3 Comparison of characteristics of the main DRI processes

	Midrex	HyL III	FIOR	Iron Carbide	FASTMET
Type of reactor	shaft	shaft	fluidised bed	fluidised bed	rotary hearth
Iron source	pellet, lump, ore	pellet, lump, ore	fine ore concentrate	fine ore concentrate	fine ore concentrate
Type of fuel	natural gas	natural gas	natural gas	natural gas	natural gas/ coal
Typical plant capacity (tmt/y)	1000	1000	400	320	450
Energy input (Gcal/mt)	2.5	2.7	4.0	3.0	3.0
Type of product	DRI/HBI	DRI	HBI	Fe_3C powder	DRI/HBI
Product metallisation	>92	>92	>92	Fe_3C >90	>92
Product carbon content (%)	1-2	1-2	0.5	< 6.0	< 2.0

CHAPTER 5 TECHNICAL DESCRIPTION OF DRI TECHNOLOGIES

Absolutum obsoletum - if it works, it's out of (Stafford Beer 1926)

5.1 Established DRI technologies

These consist of:

Gas- and liquid based:

- Midrex,
- Hyl I and III
- FIOR
- Purofer

Coal-based:

- SL/RN
- Krupp/CODIR
- DRC

5.1.1 The Midrex process

5.1.1.1 Background

The Midrex Direct Reduction Corp. Ltd. is a development and marketing company based in the USA, owned by Kobe Steel Ltd. of Japan. The Midrex process had its origin in the early development work of the Surface Combustion Corporation of Toledo, Ohio. In 1936, the company conducted laboratory-scale experiments in which iron sands from Texas were reduced with hot reducing gas introduced by "vacuum-pressure" pulsing into a bed of iron sand contained in a batch-type vessel. The reducing gas was generated by thermally cracking natural gas with steam in a refractory checker-brick regenerative stove. However, because they had no process for separating the metallised iron from the gangue satisfactorily, the project was not pursued further.

In 1948, Surface Combustion constructed a small commercial plant in Toledo to produce high-grade iron powder by gaseous reduction of mill scale. The mill scale was reduced to more than 99 per cent metallisation in batch-type retorts made from heat-resistant alloys that where heated indirectly. The reducing gas was produced by stoichiometric catalytic reforming of natural gas with steam and air using a proprietary type of reformer that has been developed by Surface Combustion for the purpose of making carburised gas for steel. After the plant had operated for about one year, it was shut down for economic reasons.

In 1959, Surface Combustion became a division of Midland-Ross Corporatic . of Cleaveland, and in 1963 they developed a process called "Heat Fast Reduction", in which green pellets made from a mixture of magnetite concentrates and pulverised bituminous coal were metallised in a direct-fired rotary hearth furnace. In this

process the pellets where spread in a thin layer, no more than two pellets deep, on the high temperature hearth of the furnace and heated very rapidly so that the carbon monoxide produced by the reduction reaction protected the pellets from reoxidising under the oxidising atmosphere of the direct fired furnace.

In 1965, a pilot plant was constructed in Cooley, Minnesota, to produce 60 to 90 per cent metallised pellets for blast furnace use, but in 1966 the project was discontinued for economic and technical reasons.

Finally, in 1966, Surface Combustion initiated the development of the Midrex process using the two key technologies in which they already had 20 years of industrial experience, namely: stoichiometric reforming of gas and counterflow-type shaft furnaces.

The first commercial MIDREX DRI plant consisted of two modules with 3,6 meter interior-diameter shafts with a combined capacity of 0,3m tpy, built for Oregon Steel Mills in 1969. In the years following, several larger units were built such as Georgetown's MIDREX 4000 unit with a 4,9 meter diameter shaft and capacity of 0,4m tpy. The world's first Midrex MegaMod 1000 module was built in 1991 by Ispat in India (Huskonen [44]).

5.1.1.2 Raw materials

The iron-bearing raw material for the Midrex process can be **iron ore pellets, briquetted ore fines** or **lump ore.** However, the type of raw material used can have an effect on the operating performance. Currently, most producers use roughly 80 per cent pellets and 20 per cent lump (CRU [22]). Some lump ores will decrepitate during reduction and generate fines that decrease efficiency of the operation and lower the overall yield. Midrex plants that are operated with 100 per cent good iron oxide pellets have produced as little as 2 per cent fines, and plants using lump ore have generated as much as 15 per cent fines. The most desirable materials are those with low gangue contents and a sulphur content below 0,01 per cent.

5.1.1.3 Equipment

The Midrex process is based on the principle of counter-current flow in which the iron-oxide material descends through a shaft furnace, where it is heated and reduced by a rising stream of hot reducing gas.

The **shaft furnace** has a circular cross section and comprise a refractory lined upper reduction shaft extending for more than half the height of the furnace and an uninsulated lower inverted conical cooling section. Midrex typically designs a shaft furnace for a specific production rate of 7 to 8 t/m^3 per day, although some of their plants have achieved specific production rates of up to 12 t/m^3 per day.

Table 5.1 Midrex shaft furnace capacities

	1	2	3
Diameter (m)	5,0	5,5	6,5
Capacity (t/y)	550 000	750 000	1 000 000

Table 5.1 shows the production rates that can be achieved by different diameter furnaces (Lepinski [62]).

The process starts with the reformation of natural gas and carbon dioxide inside the tubes in the **reformer** and then feeding this gas into the shaft furnace for reaction with iron ore. The reformer is a large, gas heated unit in which there are a few hundred or even, as in some newer megamod units, over 500 tubes.

There is a **conical hopper** at the top of the furnace that receives the charge material and feeds it to a chamber that distributes it to a multiplicity of feed pipes through the roof of the furnace to provide uniform distribution. The top of the furnace is sealed by keeping the feed pipes full of solids and supplying a small amount of inert gas into the feed pipe to prevent escape of reducing gas and infiltration of air.

The hot reducing gas is introduced through **entry ports** spaced around the furnace about one-third of the distance up from the bottom of the refractory-lined portion of the furnace. The ports are arranged on an angle so that solids cannot flow into them and cause plugging. Spent reducing gas leaves through an exit port at the top of the shaft. High-efficiency **scrubbers and packed cooling towers** clean the process off-gas before it is reused.

Entry ports for the cooling gas are located midway in the conical section in the lower part of the furnace. **Exit ports** for withdrawing this gas are located at the top of the conical section. High-efficiency **scrubbers** and packed tower **coolers** clean and cool this gas before it is recycled by means of a blower.

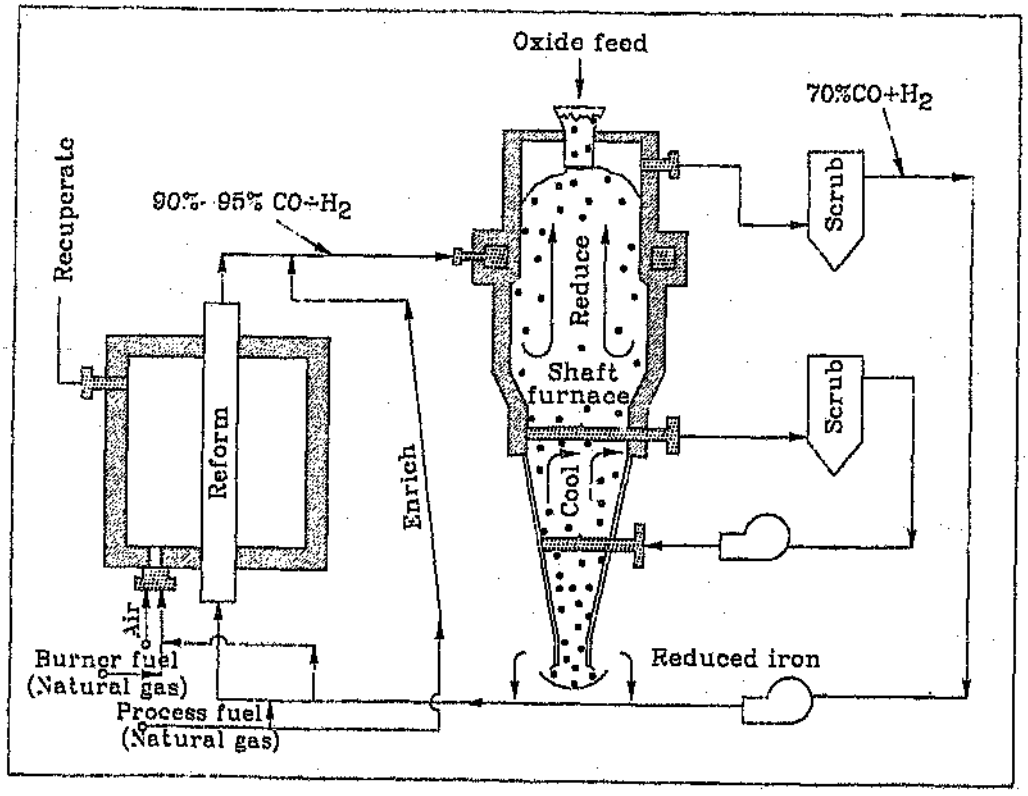
5.1.1.4 Operating procedure

In the Midrex process the reducing gas is generated in a catalytic reformer using a mixture of natural gas and process off-gas. The reducing gas is nearly 95 per cent H_2 and CO with a ratio of H_2 to CO of 1,5 to 1,6. This ratio is maintained by controlling the H_2O saturation temperature of the cooled process off-gas. To obtain the proper mixture of natural gas and process off-gas, the natural gas rate is controlled from the residual CO_2 content in the hot reformed gas.

As the reducing gas leaves the reformer its temperature is generally too high for the reduction furnace and must be lowered to about 850 to 900°C by means of a by-pass containing a gas-cooling unit. Natural gas can also be added to the reducing-gas main to control the carbon content of the product by the catalytic cracking of the methane into hydrogen and carbon when it comes in contact with the DRI in the lower portion of the reducing zone.

The reducing gas enters the furnace at the bottom of the reduction zone and is withdrawn at the top of the shaft (hence the name top gas). This gas then passes through a scrubber and cooler, after which it contains about 70 per cent H_2 and CO. It is then used for firing the reformers and for mixing with natural gas to make the process gas mixture that is fed to the reformers.

Figure 5.1 Midrex Standard Flowsheet



The charge takes about six hours to pass through the reduction zone, where it is pre-heated and reduced by countercurrent contact with the reducing gas. As the metallised material (92-95% Fe) passes down through the conical section, it is cooled by inert gas (CO and CH_4). Because the hot DRI leaving the reduction zone is a good reforming catalyst, a controlled amount of natural gas mixed with process off-gas is added to the cooling gas. The reforming reaction, which is endothermic, helps to cool the hot DRI and provides additional hot reducing gas, some of which enters the reduction zone where its heat and reducing power are recovered. In this manner the amount of reducing gas required from the reformer can be decreased by 8 to 10 per cent. The DRI is cooled to about 50-100° C before it is discharged. In the case where HBI is produced the cooling gas circuit is eliminated and hot DRI is fed to a briquetting machine.

case where HBI is produced the cooling gas circuit is eliminated and hot DRI is fed to a briquetting machine.

5.1.1.5 The DRI product

The following table shows the typical DRI product analyses according to Rose and Walden [82].

Table 5.2 Midrex DRI product analyses

Plant location	Range from different plants
Chem. Analysis (% by wt.)	
Fe, tot.	91 - 93
Fe, met.	83 - 88
FeO	-
Metallisation (%)	92 - 95
SiO_2	2,0 - 3,5
Al_2O_3	0,5 - 1,5
CaO	0,2 - 1,6
MgO	0,3 - 1,1
S	0,005 - 0,015
P	0,02 - 0,04
C	1,0 - 2,5

5.1.2 The HYL Process

5.1.2.1 Background

A shortage of steel scrap in Mexico in the early 1950's prompted Hojalata y Lamina SA (HYLSA) to seek methods of producing an alternative steelmaking material. In 1952 and 1953, they experimented with a tunnel-kiln DR process that employed "saggers" in which iron ore and reductant coal where subjected to a 44-hour heating cycle. Although the process was technically successful, it showed very poor economic prospects and was abandoned.

In 1953, HYLSA began investigating a process in which reduction was carried out in batch-type retorts using hydrogen gas flowing under a pulsating pressure. A 50 ton per day pilot installation failed to perform according to expectations, and the operation of this plant was suspended in 1953. HYLSA then undertook a fundamental investigation into all the aspects of direct reduction of iron ore in conjunction with M.W. Kellogg Company based on steam reforming of natural gas and fixed bed reduction reactors.

In 1955, a pilot plant was constructed at Monterrey, in Mexico, that gave encouraging results. This was followed in 1957 by a four reactor prototype unit employing gas quenching and reheating between primary and secondary reduction

stages. The metallised product was dumped hot by inverting the reactor. This prototype plant provided the information required to design the first commercial HYL plant, which was built in Monterrey in 1960. This module, like a number of other HYL I plants built throughout the world, have since been dismantled or destroyed either due to obsolescence (most being converted to HYL III modules) or war (Iraqi units destroyed in the Gulf War). There are 11 remaining HYL I modules and 13 HYL III modules currently in operation.

The HYL I process employs a unique system of fixed-bed reactors that are cycled through various stages of treatment to produce batches of metallised product (Yañez and Alvarez [102]).

5.1.2.2 Raw materials:

The HYL process can be operated with **lump ore and/or pellets**. Proper sizing of the raw materials is important because excessive fines would result in too much resistance to gas flow and promote gas channelling and concomitant excessive variability in product metallisation. Lumps that are too large are not suitable because they will not be reduced enough at the end of the cycle.

Although most of the commercial experience with HYL plants has been based on the use of **steam reformed natural gas**, other hydrocarbon feed stocks such as **propane, butane,** or **naphtha** can be reformed to make a suitable reduction gas. **Coke-oven gas** or the gas produced by coal gasification or by partial oxidation of fuel oil is also suitable.

5.1.2.3 Equipment

Figure 5.2 shows the basic equipment which consists of a **gas reforming unit, four identical reactor vessels** and **ancillary equipment**. The gas flow is continuous and is diverted from one reactor to another by means of a manifold and valves as the treatment cycle proceeds.

In a typical plant, the reducing gas is produced by reforming desulphurised natural gas with steam in a direct-fired reformer using a nickel catalyst contained in nickel-chrome alloy tubes. The reactor vessels are circular in cross section, have domed tops, and are fitted with gas-tight charge doors at the top and bottom.

Each reactor is equipped with a fired tubular heat exchanger for heating the reduced gas to about 1100°C by combustion with a precisely controlled amount of air. The reducing gas enters at the top of the reactor, and the off-gas leaves the bottom of the reactor through a manifold between the conical bottom of the reactor and the conical baffle that supports the charge.

Each reactor is provided with a positive extraction device which is retracted below the bottom discharge door when not in use and is elevated into the reactor if required to break up bridged or fused burden material.

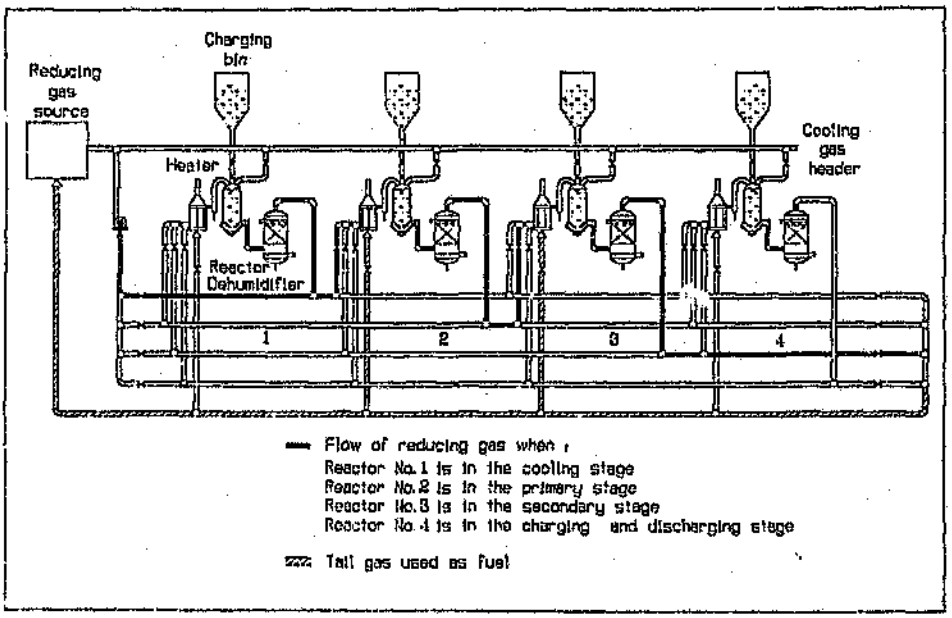
5.1.2.4 Operating procedure:

In normal operations, each of the four reactors is cycled through four stages, each stage being about 3 hours in duration. Consequently, a total of 12 hours is required for one reactor to complete the full reduction cycle.

Stage 1 -

After the DRI from the previous cycle has been discharged, the interior of the reactor is inspected and routine maintenance tasks are performed. The bottom door of the reactor is then closed and sealed, and the iron oxide is charged through the top door.

Figure 5.2 - HYL I Process Flowsheet



Coarser material is customarily charged into the bottom of the reactor to increase the permeability there and promote more uniform gas flow. Uniform burden distribution is obtained by means of a rotating distributing chute inserted into the reactor during charging.

Stage 2 -

Stage 2 is referred to as secondary reduction because it uses lean reducing gas that has already been used in Stage 3 and has lost some of its reducing power. In Stage 2 the hot reducing gas flowing through the charge pre-heats it and starts the reduction. The off-gas from Stage 3 is first quenched to remove the water vapour formed during reduction. This gas is then pre-heated to 800-850°C in the tubular heat exchanger and introduced into the partial oxidation burner where it is heated to 1050-1150°C by partial combustion with a precisely controlled flow of pre-heated air.

The hot reducing gas enters at the dome of the reactor and flows down through the iron ore charge to the bottom. In this stage, approximately 40 per cent of the reduction is accomplished. The off-gas then passes through another quencher to remove the water vapour formed during reduction. The spent gas is used as a fuel to generate steam and to fire the heat exchangers.

Stage 3 -

After the prescribed cycle time, the interlocking valves divert the lean reducing gas to the next Stage 2 reactor and initiate the flow of full-strength reducing gas into this reactor in the cooling stage (Stage 4). The gas leaving the reformer first passes through a quencher for the removal of unreacted water vapour from the steam-methane reaction, and then through the reactor that is in the cooling stage where the gas serves as the cooling medium. The gas leaving the cooling-stage reactor is also quenched to remove water vapour that may have formed there. The gas is then pre-heated to about [illegible]°C in the tubular heat exchanger and to about 1000-1200°C in the partial oxidation combustion chamber before it is admitted to the Stage 3 reactor.

Stage 4 -

In Stage 4, the cooling stage, the gas from the reformer is admitted directly into the top of the reactor. The gas is typically composed of mostly hydrogen, but also contains carbon monoxide, carbon dioxide and methane. When this rich reducing gas comes in contact with the hot DRI, additional reduction is accomplished, and the formation of iron carbide (Fe_3C) is also induced in the outer layers of the DRI lumps or pellets. With [illegible]nal cooling cycle, the carbon content of the product is between 2,2 and 2,6 per [illegible] However, the carbon content can be controlled to any desired amount between 0,8 to 2,6 per cent by isolating the cooling stage from the regular gas system and recycling a controlled composition of gas through it.

The percentage metallisation of the DRI depends primarily on the cycle time so that the production rate is a function of the per cent metallisation. In general, for most iron ores, every one per cent decrease in the metallisation, results in a 1,8 per cent increase in the production rate in the range from 80 to 90 per cent metallisation.

In the most recent HYL plants, an improvement in efficiency has been obtained by combining the pre-heaters for the reducing gas with those for the combustion air fed to the partial combustion chambers.

5.1.2.4 Newer developments

In 1979, HYLSA announced the development of significant improvements to the HYL process. These improvements **(HYLIII)** comprise design modifications that increase the efficiency of many operations such as material handling, natural gas reforming, process gas heating and overall gas utilisation. The first HYL III was built in Monterrey (the 2M5 plant) in 1979. Older original HYL III units were as small as 0,25m tpy, but currently, units are available with nominal capacities up to 1,2m tpy (CRU [22]).

Some of the **major differences** compared w[illegible] conventional HYL process are:

⇒ Grouping the reactors into **one module in a single tower** with a single charging bin and discharge hopper to facilitate material handling and reduce interconnecting piping.
⇒ More **efficient heating furnaces** that combine the natural gas reforming and process-gas heating furnaces in a single unit. Better alloys that enable continuous heating of the reducing gas to 950° C and minimise the partial combustion required for the final heating.
⇒ The **continuous process gas heating** eliminates the cyclic operation of the earlier furnaces and provides increased efficiency.
⇒ The reducing gas is transferred from the heater to the reduction reactors by **hot transfer** lines and is diverted to different reactors at the end of each operational cycle by means of hot valves which can withstand a temperature up to 950° C.

HYL no longer offers the HYL I process as a technology option, as its HYL III process is far more efficient. HYL has upgraded several HYL I modules to HYL III, which entails replacing the HYL I reactor series with one HYL III shaft furnace while maintaining the original reformer and other ancillary equipment.

Although the original HYL (batch) process did not recycle reduction reactor exit gas, or top gas, the newer HYL III (continuous) process does so to reduce energy consumption. The other gas-based processes in operation, Midrex and FIOR, also recycle their top gas, however, to keep its reduction gas low in oxidants, Midrex limits the recycling to approximately two-thirds of the available top gas.

5.1.3 The FIOR Process

5.1.3.1 Background

In the late 1950's, investigation into methods for applying fluidised-bed techniques to the reduction of fine ore was begun by Exxon Research and Engineering. In 1960, they assumed all responsibility for development of the technology they called FIOR, the acronym for Fluid Iron Ore Reduction. In 1976, a commercial size FIOR plant with annual capacity of 400 000 metric tons of DRI briquettes started operation at Puerto Ordaz, Venezuela and is still the only operating FIOR plant. This process is the only gas-based direct reduction process relying on iron ore fines as feedstock (FIOR [30]).

5.1.3.2 Raw material:

The preferred ore for the FIOR process is **earthy hematite.** The **reducing gas** is primarily **hydrogen** and can be prepared by any one of a number of processes such as catalytic steam reforming, partial oxidation, coal gasification, etc. from a variety of hydrocarbon feedstocks (natural gas, LPG, naphtha, heavy oils, etc.) and coal.

5.1.3.3 Equipment

The FIOR plant in Venezuela contains the following major pieces of equipment:

- *ore dryer* for removing surface moisture from the ore,
- *lock hoppers* for pressurising the ore feed to the pre-heat reactor operating pressure,
- *pre-heat reactor* for removing bound moisture and raising the ore temperature to the reducing reactor temperature,
- *reducing reactors*, three reactors in series in which the ore is reduced in stages by contact with counter flowing reducing gas,
- *natural gas reformer and shift converter* to convert natural gas to a reducing gas with a high H_2 and CO concentration by means of steam and catalysts,
- *CO_2 removal unit* to remove excess CO_2 from the shift effluent gas and produce a reducing gas with high H_2 concentration,
- *briquetting feed drum* to store the reduced iron ore fines at atmospheric pressure to feed to the briquetting machines,
- *briquetting machines* consisting of double roll presses with pockets in which the reduced iron ore fines are compressed into a dense, compact, pillow-shaped product,
- *trommel drums* in which the strings of briquettes from the briquetting machines are broken into individual pieces by tumbling,
- *briquette cooler*, a circular grate on which the hot briquettes are cooled and passivated with air.

5.1.3.4 Operating procedure:

Ore preparation includes transportation of fines to the Venezuelan FIOR plant site, weighing and storage. The fines are reclaimed by front end loader and loaded onto a belt conveyor which feeds a rotary drier.

The moisture level is reduced to approximately 0,2 per cent by weight, and the ore is then conveyed to a dry ore storage bin. The dried ore is removed from this storage bin through a weight hopper which discharges into a skip hoist. The skip hoist lifts the ore to the top of the reactor structure and pressurises it to the operating pressure. The ore reduction system operates at about 10 atmospheres pressure and 880°C.

Ore Reduction System:

Pressurised, dried ore is metered from the lock hoppers into the uppermost of the four reactors. In this reactor, the ore is pre-heated to reduction temperature by combustion of natural gas and pre-heated air in the fluidised iron ore bed. The remaining moisture is driven from the ore and carried off with the flue gas from the reactor. The flue gas is quenched and scrubbed to remove iron ore fines. The cleaned flue gas is depressurised and released to the atmosphere.

Fluidised, pre-heated iron ore flows from the pre-heat reactor into a standpipe where it is steam stripped to remove entrained air, and metered by a cycling slide valve into the uppermost reduction reactor.

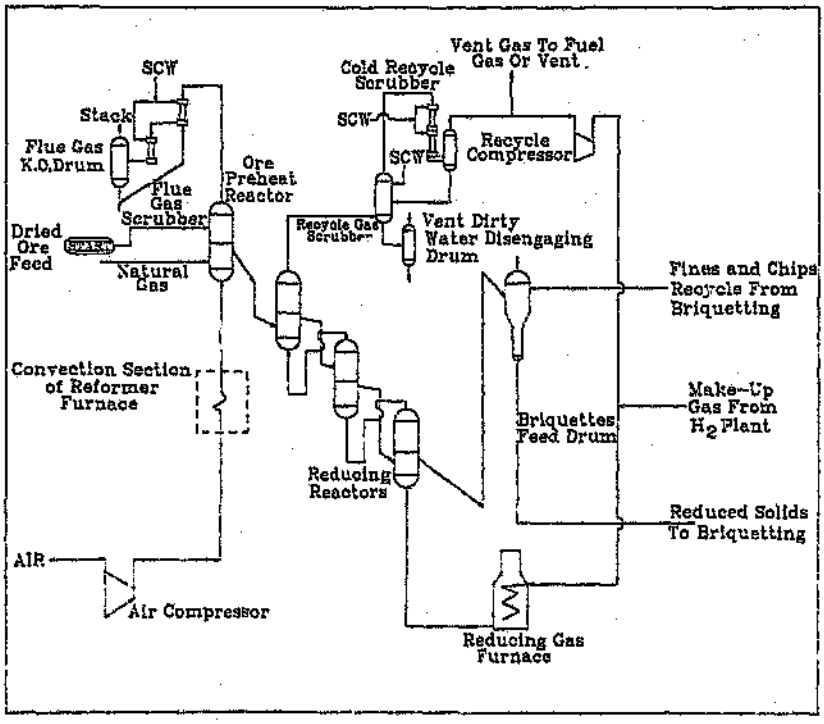
There are three fluid bed reduction reactors in series. The iron ore flows downward through them by gravity and the flowing ore is maintained in a fluidised state, while

at the same time, reduced by the circulating reducing gas. This reducing gas flows upward through each of the reducing reactors counter-current to the descending ore. Internal cyclones minimise the entrainment of ore fines from the fluidised beds.
The spent reducing gas leaving the upper reducing reactor is quenched and scrubbed to remove the water produced by reduction and to remove fines carried in the gas from the cyclones. The cool, scrubbed gas is compressed, combined with fresh make-up gas from the hydrogen unit, sent through a reheat furnace and finally returned to the lower reduction reactor. A small quantity of the compressed recycle gas is sent to the plant fuel gas system to purge inerts and provide pressure control. Water from the scrubbing systems is depressurised and then sent to retention ponds where the entrained ore particles are settled and reclaimed.

Reduced iron ore fines from the lower reduction reactor are depressurised through a product let-down system into the briquetter feed drum, operating at atmospheric pressure.

Briquetting is done hot, close to reduction temperatures, using double roll presses. These machines produce strands of dense, highly compacted pillow shaped briquettes which are discharged into trommels where the strands are broken apart.

Figure 5.3 - FIOR Process Flowsheet



A screen section in the trommel separates the briquettes from the fines and chips. The latter are recycled to the briquetter feed drum. The hot briquettes from the

trommels are cooled and air passivated on a circular grate cooler and then conveyed to open storage piles.

The make-up reducing gas stream added to the recycling reducing gas stream is primarily hydrogen. This hydrogen rich stream is produced by steam reforming natural gas over a nickel catalyst packed into the reforming furnace tubes. Prior to reforming, the natural gas feed is desulphurised over zinc oxide beds.
The reformed gas is shift reacted using an iron oxide catalyst that converts carbon monoxide to carbon dioxide and hydrogen in the presence of steam. The carbon dioxide is then removed from the gas stream by contact with a circulating hot carbonate solution. The final hydrogen rich gas stream is then added as make-up gas to the recycling reducing gas stream.

The FIOR briquettes contain about 92 per cent total iron and are 92 to 94 per cent metallised.

5.1.4 Purofer Process

5.1.4.1 Background

Prior to 1961, the former Huttenwerk Oberhausen AG, now a subsidiary of Thyssen, called Thyssen Niederrhein AG, experimented with the reduction of iron ore on a small pilot travelling grate using reducing gas made from the reforming of natural gas. In 1961, they replaced the travelling grate with a small pilot shaft furnace, and in 1970, they constructed a semi-commercial shaft furnace plant with capacity of 500 t per day at Oberhausen. This plant was originally equipped to generate its reducing gas by reforming natural gas with air, but later was changed to accommodate reforming natural gas with process off-gas.

In 1976 and 1977, two commercial Purofer plants, each with a capacity of about 350 000 tons per year, where put into operation, one in Iran, and the other in Brazil. At the plant in Brazil, the reducing gas is made from heavy fuel oil. Late in 1979 this plant was shut down for economic reasons.

5.1.4.2 Raw material

The Purofer process can be operated with either **pellets or lump ore.** At the plant in Iran, oxide pellets are used, and there is very little difference between the size of the charged pellets and that of the DRI product. However, at the plant in Brazil, where the charged domestic lumpy ore is sized to minus 32 mm plus 6 mm, there is some degradation during the reduction.

The source of energy for the reducing gas can be **natural gas, coke oven gas, fuel oil, or coal.** However, the only fuels used are natural gas, coke oven gas and fuel oil.

5.1.4.3 Equipment

In the Purofer process, the reduction furnace is a **refractory-lined shaft.** The cross section of the shaft is rectangular, but the corners are rounded. At the top, the shaft consists of a **double bell charging system,** similar to a blast furnace.

The shaft tapers outward from top to bottom, with the bottom hosting two **scraper bars** which remove the hot reduced product from both sides of the shaft. The hot material falls into the **collection hopper** which has a gas-tight connection with the bottom of the furnace.

A **double lock-hopper** at the bottom of the collection hopper is used to extract the product into sealed steel containers without exposing the product to air. By these containers the Purofer iron is transported to a **briquetting press** for compacting the still hot product to increase its density and minimise dust forming and reoxidation. At the plant in Brazil, the hot DRI can be transported without briquetting directly to the steelmaking furnace for hot charging.

The reducing gas at the Brazil plant is generated by reforming heavy fuel oil with oxygen and steam using the **Texaco Partial Oxidation process.** There are **pre-heaters** for heating the oil and oxygen before they are fed into the burner of the partial oxidation reactor. The raw gas leaving the reactor is cooled in a waste heat boiler and then scrubbed to remove firstly soot and then sulphur and CO_2. **Coolers and scrubbers** are also located near the outlet of the off-gas from the shaft furnace to remove water and CO_2 from this gas. The gas is then mixed with the gas from the reformer, where a recuperative gas heater heats the mixture to the desired temperature before it is introduced into the shaft furnace.

5.1.4.4 Operating procedure

In the Purofer process the iron bearing material, either pellets or lump ore, is charged into the top of a shaft-type furnace and descends counter-current to the flow of hot reducing gas which heats and reduces the charge. The residence time of the iron bearing materials in the furnace is controlled by the rate at which the scraper bars remove the hot reduced product from the bottom of the shaft.

At the **Iranian plant,** the off-gas from the shaft furnace is cleaned and cooled to remove water vapour, and then mixed with natural gas in the reaction

$$\Rightarrow \quad CO_2 + CH_4 = 2CO + 2H_2$$

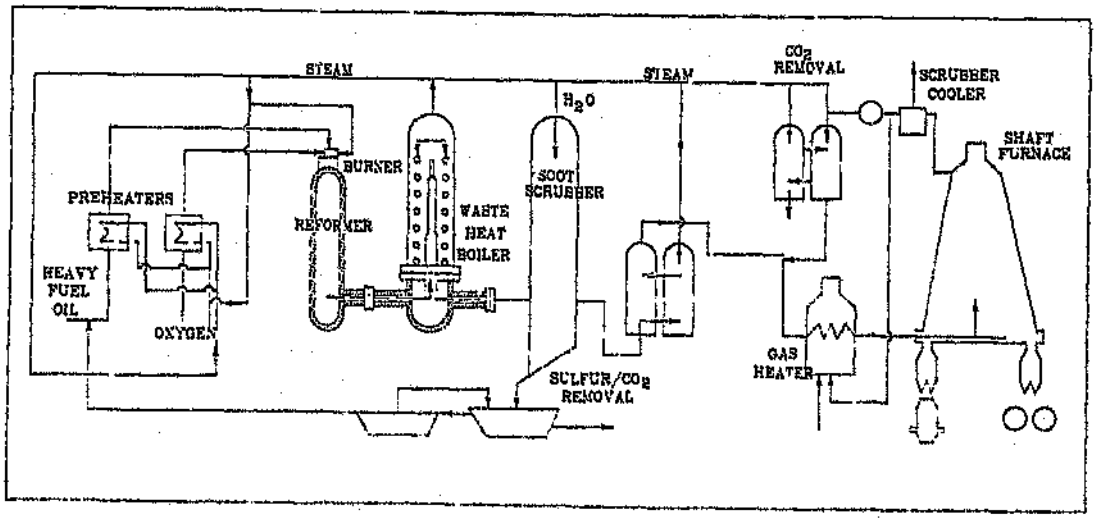
This mixture is then fed into one of the catalytic reformers that has already been heated to 1400°C, where it is reformed into a reducing gas containing about 95 per cent hydrogen and CO. Due to the endothermic character of the reforming reaction, the temperature of the reformer decreases. When the temperature has dropped to 1200°C, the mixture of natural gas and process off-gas is switched to the other reformer which has been reheated from 1200°C to 1400°C by the combustion of a portion of the off-gas during the concurrent heating cycle. During reforming, sulfur from the natural gas is deposited on the catalyst, but during the reheating, the sulfur is oxidised and removed with the off-gas.

The reducing gas leaving the reformer is cooled to about 950-1000°C or whatever is required to prevent sticking of the charge. At the plant in Iran, all of the DRI product leaving the shaft furnace is briquetted while it is still hot to give it a density of about 5,4 g/cm3.

At the **plant in Brazil**, the reducing gas is generated by reforming heavy fuel oil with oxygen and steam using the Texaco Partial Oxidation process. The raw gas is produced at 1400°C and is then cooled and scrubbed to remove the soot, the sulfur and the CO_2. This gas is then mixed with a portion of the process off-gas which has been cooled to remove water vapour and also scrubbed to remove CO_2. This mixture is then heated to the desired temperature (about 1000°C) for the shaft furnace in a gas heater fired by a portion of the process off-gas. Due the the fact that he CO/H ratio in this reducing gas is greater than that obtained when the reducing is made from natural gas, it is necessary to have a higher degree of oxidation of the fresh reducing gas to prevent carbon depositing in the gas heater.

In the Brazil plant, the DRI product can be transported directly to the electric steelmaking furnaces while it is still hot, or it can be briquetted for storage. Because the reducing gas made from fuel oil must be cooled and then reheated, the energy requirements for the fuel-oil plant are higher than for the natural-gas plant.

Figure 5.4 Purofer Process Flowsheet



5.1.5 The SL/RN Process

5.1.5.1 Background

The full name of the SL/RN process is Stelco, Lurgi, Republic Steel, National Lead process. It was developed as a combination of the Republic Steel, National Lead (RN) process, which originated between 1920 and 1930 for the beneficiation of low-grade ores, and the Stelco, Lurgi (SL) process, which was conceived in around 1960 for the production of high-grade direct reduced iron (DRI). The RN process can be considered as a modification of the Krupp-Renn process, which was also a rotary kiln process for the beneficiation of low-grade ores.

The **major differences** between these two processes were:

- the RN process was operated at a lower temperature so that melting of the charge materials did not occur,
- the RN process employed a basic flux to combine with the sulphur of the fuel and solid reductant so that less of the sulphur would combine with DRI.

The SL/RN process is currently the leading coal-based DR process.

5.1.5.2 Raw materials:

The principle **burden material** for this process is **iron-oxide pellets** but **lumpy ores** can also be used. The following table shows typical characteristics of various ores which can be used as feedstock (Rose and Walden [82]).

Table 5.3 Typical characteristics of iron bearing feed in SL/RN plants

Plant location	AFP Brazil		NZS New Zealand	WSL Australia	ISCOR South Africa	BSIL India
Ore type	lump	pellet	beach sand	Ilmenite	lump	lump
Chem. Comp. (% by wt.)						
Fe, tot.	69,4	68,2	57,8	27,0	66,0	67,4
SiO_2	0,58	1,2	3,7	1,0	2,5	1,5
Al_2O_3		0,5	4,2	0,9	1,3	1,0
CaO	0,03	0,8	1,1		0,2	-0,05
MgO		0,3	3,1	0,15		-0,05
TiO_2			7,8	58,5		
S		0,005	0,04		0,009	0,009
P		0,02	0,06		0,04	-0,03
Grain size (mm)	5-15	5-20	-0,5	-0,5	5-15	5-15

A wide range of **fuels and reductants**, such as **lignite, char, low temperature coke, coke breeze** and **anthracite coal** can be used. Some of the typical feeds are shown in table 5.4 (Rose and Walden [82]).

Table 5.4 Typical composition of coals used in SL/RN plants

Plant location	AFP Brazil		NZS New Zealand	WSL Australia	ISCOR South Africa	BSIL India
Coal type	**Bituminous**	**Lignite**	**Lignite**	**Coke breeze**	**Sub. Bitum.**	**Sub. Bitum.**
Prox. Analys. (% by wt.) Fixed carbon	40	45	49	81	58	50
Volatiles	25	51	42	3	28	25
Ash	35	4	9	18	14	25
Sulphur (% by wt.)	0,4	0,3	0,3	0,7	0,6	0,6
Moisture (% by wt.)	9	17	18	1	6	10

5.1.5.3 Equipment

Rose and Walden [82] explain how the reduction in the SL/RN process is conducted in a **refractory-lined rotary kiln**, mounted with a slope downward from the feed end to the discharge end.

5.1.5.4 Operating procedure:

At the start-up of an SL/RN operation, it is necessary to fire the kiln with the central burner, using any convenient fuel, to bring the charge material up to reaction temperature. After this is accomplished, a steady state is attained in which the heat produced by the combustion of a portion of the fuel charged with the burden is sufficient to raise the temperature of the incoming material to the desired level.

There are two major steps in the process which correspond to the two major zones in the kiln.

- The first is the **pre-heat zone** where the charge is heated to 900-1100°C.
- The second is the **metallisation zone** which is held fairly constant at 1050-1100°C.

The charge into the kiln consists of a **mixture of iron oxide pellets and/or small lump ore, limestone** and/or **dolomite**, and **high-volatile coal or lignite.** In the pre-heating zone, moisture is driven of first, and then, hydrocarbons and hydrogen are

formed by the thermal decomposition of coal. As the combustible gases from the coal rise from the bed of solid material, portions of these gasses are burned in the freeboard above the bed by the controlled quantities of air that are introduced through the air pipes spaced evenly along the kiln.

The combustion of these gases in the freeboard radiates heat to the surface of the bed of material and also to exposed surface of the kiln lining. As the kiln rotates (about 0,25 rpm), the lining carries this heat down into the bed and transfers it to the solid materials.

In the pre-heat zone, the reduction of the iron oxide proceeds only to the ferrous oxide (FeO) level. The final reduction to metallic iron takes place in the metallisation zone.

The off-gasses from the kiln are drawn out through the feed end of the kiln at 900°C to 1000°C. These gases pass through a coarse gas settling chamber and then into an afterburner where first the combustible gasses are burned and then most of the small particles of soot are burned. The gas is then cooled and cleaned and exhausted to the stack.

The solids discharged from the kiln go through an enclosed chute to the rotary cooler where they are cooled to about 100°C without coming in contact with air. A grizzly located in the chute removes accretions that are large enough to plug up or damage the cooler discharge mechanism.

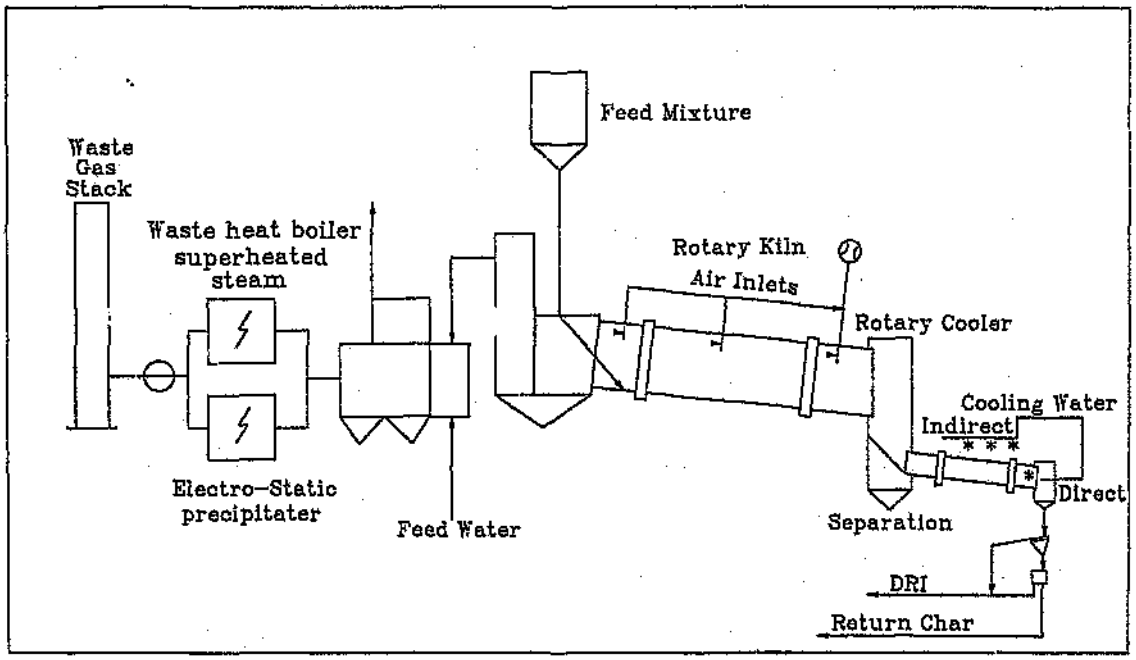
The material leaving the cooler is screened to remove the +30mm DRI. The undersize, which is a mixture of DRI, calcined flux, char, and coal ash, is separated by screening into a plus and minus 3mm fraction. Each fraction passes through a magnetic separator where the non-magnetic portion of the +3mm fraction is mostly calcined flux, ash, and fine char and is discarded.

The magnetic portion of each fraction is DRI product. The +3mm fraction can generally be used directly for steelmaking, whereas the finer fraction must be briquetted before it can be used for this purpose.

Table 5.5 Typical DRI product composition

Plant location	Iscor-South Africa	BSIL-India
Chem. Analysis (% by wt.)		
Fe, tot.	90,4	93,7
Fe, met.	84,0	86,7
FeO	8,1	9,64
Metallization	93	92
SiO_2	5,8	2,4
Al_2O_3	1,8	1,8
CaO	0,3	-0,05
MgO	-	-0,05
S	0,01	0,02
P	0,05	-0,04
C	0,1- 0,2	

Figure 5.5 SL/RN Process Flowsheet



5.1.6 The Krupp/CODIR Process

5.1.6.1 Background

Krupp's experience with rotary-kiln technology began in the mid-1920's when they installed a rotary-kiln process, called the Waelz process, to recover zinc from low-grade ores. Based on the experience with coal-fired kiln operations derived from the Waelz process, Krupp developed a process to recover iron from ores with low iron and high silica content. Cunningham et al [23] explain that the Krupp-Renn process made it possible to use low-grade lump iron ores and a variety of carbonaceous fuels, such as coal, coke and char, to produce a highly (98%) metallised product that could be used in iron and steelmaking processes.

Meyer [63] explains how the rotary kiln was fired from the discharge end with pulverised coal or fuel oil so that the gas flowed counter-current to the ore flow. In its passage through the kiln, the ore was pre-heated, reduced and the gangue fused into a mobile slag. After the material was discharged into water, it was crushed and separated magnetically and by screening into three fractions:

- coarse magnetic metallic particles called "luppen",
- coarse non-magnetic char particles that were recycled,
- and a magnetic material of intermediate size that was recycled.

The energy requirements for producing "luppen" from high gangue ores was as high as 10Gcal/mt of "luppen". This high energy requirement, along with the increased availability of high-grade iron ores at relatively low cost, brought about the gradual abandonment of this technology for processing iron ore.

From the experience of both the Waelz and the Krupp-Renn processes, the Krupp DR process, which is known as CODIR (Coal-Ore Direct Iron Reduction) process, emerged.

Using the existing Krupp-Renn plant in Germany, 15 000 tons of high-grade DRI was produced from Brazilian lump ore and coal. The success of this operation and the subsequent successful use of the product in steelmaking trials encouraged Krupp to commission a semi-commercial pilot plant to investigate the use of a wide variety of feed materials and fuels.

5.1.6.2 Raw materials:

The Krupp CODIR process permits both **high-grade lump ore and pellets** to be converted into metallised products, mainly using solid fuels.

Some of the reductants that have been tested are **coke breeze, petroleum coke, low-temperature coke**, and **coke from lignite**. Fuels for heating that have been tested successfully include **natural gas, coke oven gas, oil, and pulverised coal.**

The raw materials used at Dunswart Iron and Steel Ltd. are a good example of the type of materials used in a Krupp plant operating with lump ore. At this plant, a rich South African hematite ore is used that has an iron content between 66 and 68 per cent. The reductant is South African anthracite coal.

5.1.6.3 Equipment

The ore and pellets are fed into an **inclined kiln** together with the reductant and sulphurising agent and heated (counter-current) by the hot kiln gases and metallised into DRI. The material delivered by the kiln is a mixture comprising metallised iron, surplus fuel, desulphurising agent and ash. This mixture is subjected to direct and indirect water cooling in a **rotary cooler.** Subsequent treatment is carried out by combination of **screening, magnetic separation, and gravity separation** facilities.

The kiln is heated from the discharge end in a deficiency of air. Over its entire length, the kiln shell accommodates **tuyeres** permitting air to be blown into the kiln, mainly to burn the carbon monoxide evolving during reduction as well as part of the volatile matter in the coal. Thus, a uniform temperature of between 950 and 1050°C can be maintained in the feed over the length of the kiln.

The CODIR process features a high flexibility in using different types of non-coking coals such as bituminous, sub-bituminous, and anthracite coal.

In the Krupp plant at the **Dunswart Iron and Steel Limited** in Benoni, South Africa, that was put into operation in 1973, the reduction kiln is 73,5 meters long and 4,6 meter in diameter. The kiln is mounted with a 2,5 per cent downward slope from

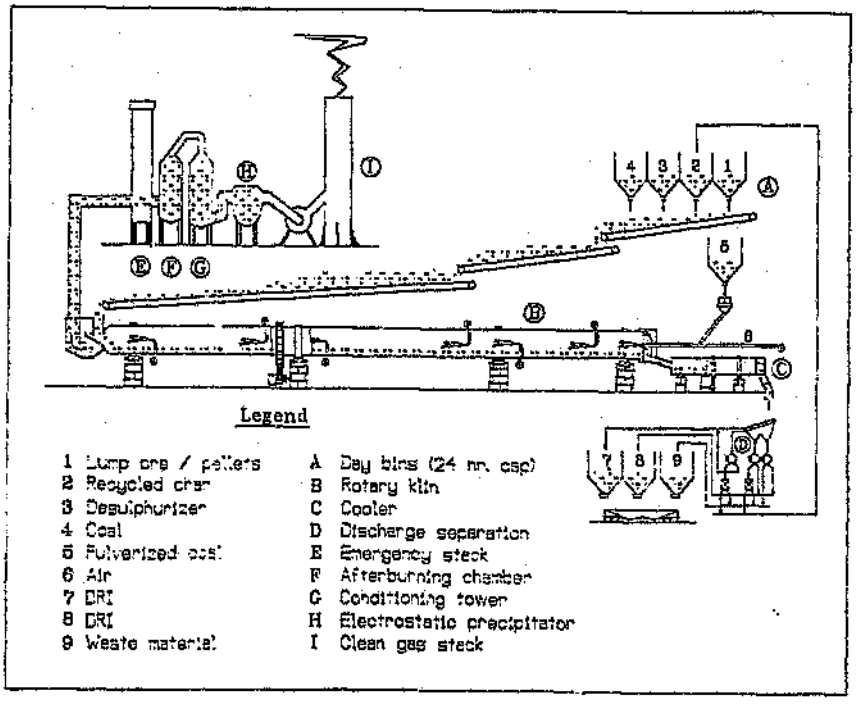
entre .e to exit and can be rotated at speeds between 0,35 and 0,8 rpm. There are six shell-mounted fans to provide air to the burner tubes that enter through the shell and discharge the air along the centre line of the kiln in the same direction as the direction of the flow of the exhaust gases. The kiln off-gas passes first through a dust settling chamber where high pressure water sprays initiate cooling. The gas is further cooled to about 170°C for final cleaning in a bag filter. The cooler at this plant is 13m in length and 2,5 m in diameter. Helical guides transport the material through the cooler.

5.1.6.4 Operating procedure

For the operation of the Krupp CODIR process on lump ores, the ore and the desulphurising agent are fed into the reduction kiln t ,ther with high- or low-volatile coal, anthracite or coke breeze, and recycled char.

The kiln is heated by a burner at the discharge end using pulverised coal, fuel oil, or gas, which is burned with a deficiency of air to create a reducing atmosphere in the kiln. The flow of air through the inlet tubes spaced along the length of the kiln is adjusted to control the combustion of the CO formed from the reduction reaction and the volatiles from the coal. In this way the temperature in the kiln for more than 60 per cent of its length, starting from the discharge end, is kept in the range of 950°C tc 1050°C. The gas temperature at the charging end drops to about 800°C.

Figure 5.6 KruppCODIR Process Flowsheet



Most of the metallisation takes place in the final 50 per cent of the kiln length, and DRI is discharged at 1050°C. Direct and indirect water sprays cool the material to a temperature of about 150°C, with cooling proceeding very rapidly through a particular temperature range to avoid reoxidation.

Due to the high temperature of the reduction and the formation of a thin surface layer of oxide during quenching, the DRI is relatively inert to atmospheric oxidation. At Duiswart, the metallisation of the DRI is between 90 and 94 per cent, the sulphur content averages 0,03 per cent, and carbon averages 0,1 per cent. The total energy requirement for heating and reduction is between 3,8 and 4,0 Gcal/mt of DRI.

5.1.7 Davy DRC® Process

5.1.7.1 Background

The Davy DRC® process was developed by the Direct Reduction Corporation (DRC), which is a division of Davy McKee, with its origin in development work done by Western Titanium Ltd., Australia, to produce synthetic rutile by reducing ilmenite with coal. This company (Davy International) also licences the FIOR and HYLIII technologies. After the technology was developed, it was later used for making DRI in what was called the Azcon process in 1978 at Rockwood, Tennessee. The name of the process was later changed to DRC after the newly formed company took charge of its operation and marketing.

The DRC process is a **coal based rotary kiln technology**, similar in principle to the SL/RN process that uses lump iron ore or pellets, together with limestone or dolomite flux, and solid carbon as reductant.

5.1.7.2 Raw materials

In the DRC process, iron ore is used sized to minus 20-mm plus 5-mm (Haworth[39]). Lump ore should be relatively strong without disintegration during reduction. Coal used in the process should have both a high ash-fusion temperature and high char reactivity. Sulphur in the coal should not exceed 2 per cent. Limestone is used to desulphurise the mixture. The product resulting from the mix has a metallisation in excess of 92% and sulphur below 0.02%.

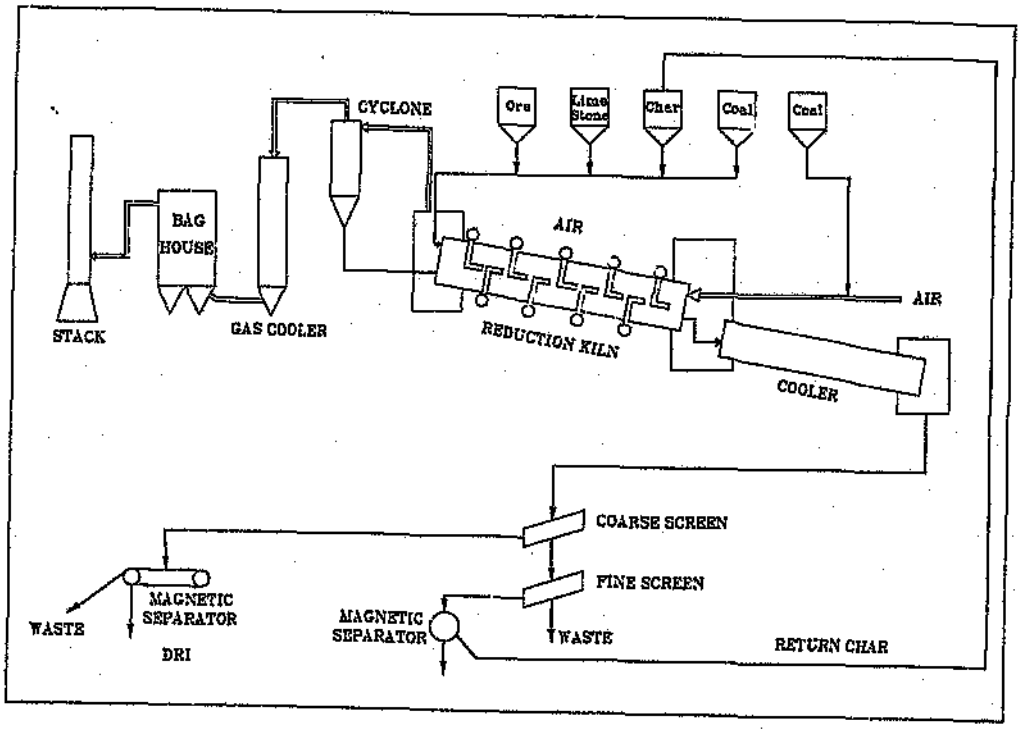
Haworth [40] states that Scaw Metals has a two module 0.18m tpy DRC plant that was built in the 80's at Germiston, South Africa. The plant, which is currently still in operation, regularly exceed design capacity. There, a low ash-bituminous pea coal is used as reductant with 57% fixed carbon and 28% volatiles. The iron charge used is either 100% lump or 100% pellet.

5.1.7.3 Operating procedure

Material from the raw materials bins is fed through a refractory lined kiln sealed at both ends to prevent the entrance off air. Airports along the length of the kiln supply combustion air for gas burning in the kiln as well as controlling the kiln temperature. Product from the kiln is discharged into a rotary cooler through a transfer chute.

Following the cooler is a station for product screening and magnetic separation. Kiln off-gas is passed through a cyclone to remove coarse dust, and is then cooled and passed through bag filters to remove fine dust.

Figure 5.7 DRC Process Flowsheet



5.2 New and Developing Technologies

5.2.1 Midrex upgrades

The original Midrex plant design with rated capacity of 0,3m tpy and 3,6 meter interior shaft diameter has been upgraded several times since its inception. After increases to 0,4m tpy and 4,9 meter diameter, currently a "Stretch Megamod" unit now offers a nominal capacity of 1,36m tpy (6,65 m diameter) and the "Super Megamod" up to 1,5m tpy (7,5m diameter) Midrex has since seen various generations of enlargements with the largest unit currently offered being a 6,65 meter interior diameter furnace called the MIDREX Stretch Megamod™ unit. An even larger 7,5m-diameter furnace, called the Super Megamod™, is currently in the designing stage.

Figure 5.6 New Midrex Module Specifications

Plant model	Nominal capacity (million tpy)	Shaft Diameter (meters)	Design year
Midrex Minimod™	0.25 - 0.35	4.25	1969
Midrex™ Series 500	0.35 - 0.55	5.00	1974
Midrex™ Series 750	0.55 - 0.80	5.50	1980
Midrex Megamod™	0.80 - 1.20	6.50	1990
Midrex Stretch Megamod™	1.20 - 1.36	6.65	1997
Midrex Super Megamod™	1.36 - 1.80	7.50	1998

5.2.2 SPIREX™ Process

5.2.2.1 Background

Midrex together with Kobe have developed a new gas-based SPIREX™ (spouted iron reduction) process, using iron ore fines to produce DRI or HBI. Development was announced in 1996 and construction is underway of a $14m, 30 000 tpy pilot plant near OPCO in Puerto Ordaz, Venezuela. The process will be tested in the demonstration plant to be built in late-1997 at the OPCO plant in Venezuela. Hassan and Whipp [36] indicated that the SPIREX plant will use process gas generated in OPCO's Midrex gas and pellet/lump based reformer, and iron ore fines produced locally.

5.2.2.2 Operating procedure

The process, which resembles the Circored process, uses a **circulating fluidised bed pre-heater** and a **two- stage reactor,** with the initial stage being a **circulating fluidised bed reactor** and the second stage a **bubbling fluidised bed reactor.** Reducing gases are generated in a conventional Midrex reformer.

Dried and screened iron ore fines are fed to a pre-heater for preheating and pre-reduction using off-gases from the two reactors. Reduction of fines to a smaller and more uniform size is attained by turbulent movement of iron ore fines in the preheater and the first stage reactor. High speed gas currents in the first stage prevents the sticking and clogging phenomena commonly experienced at fines based plants

After about three hours of residence time, the two stage process reduces iron ore fines at 800-850°C to an expected minimum metallisation of 92 per cent (CRU [22]).

5.2.3 Fastmet™ Process

5.2.3.1 Background

Midrex has also developed a new technology in an attempt to develop a DR process that could use the abundant coal reserves of North America (Griscom and Lyles [36]). Fastmet™ is a **rotary hearth-based** process and is similar to the INMETCO process in feedstock, hardware and process flow. Midrex and Kobe Steel Ltd., have constructed and are operating a demonstration-scale plant in Japan.

A first commercial-scale FASTMET plant, the KM Iron project, are planned by Kobe Steel and Mitsui and will be located near the Mississippi River in Louisiana.

5.2.3.2 Raw materials

A wide range of **hematites, magnetites, ilmenites, iron sands, and waste oxides** can be successfully used in the process. The process accepts oxide fines in the size range of pellet feed (80% - 325 mesh).

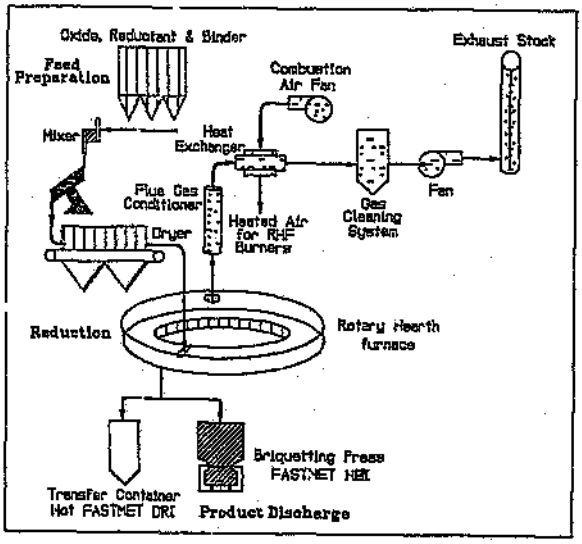
Most coals, cokes, and chars having less than 20 per cent ash and at least 50 per cent fixed carbon can be used as reductant if a dryer is used. The preferred reductant size is 70 to 80 per cent minus 200 mesh (Lepinski [51]).

5.2.3.3 Operating procedure

Lepinski and Griscom [53] describe the process as follows: Pulverised reductant (coal, coke or char) and iron ore fines (sized to 80% minus 200 mesh) are mixed together with a binder, and pelletised. Resulting green pellets are fed either to the drier to remove moisture (120°C), or directly to the rotary hearth furnace, where pellets are placed on the rotating hearth in an even layer, one to three pellets deep.

In the rotating furnace, pellets are heated to 1250-1350°C using gas, oil or coal-fired burners and the iron ore is reduced to metallic iron. Inside the pellets, reduction occurs simultaneously with the generation of reducing gas ($CO_2 + C \Rightarrow 2CO$). As pellets are heated, carbon from the reductant is converted to carbon monoxide, which then reduces the iron oxide to metallic iron. Very rapid reduction takes place due to the intimate contact of iron oxide and carbon, as well as the high reduction temperature. A typical residence time in the furnace is 6 to 10 minutes, varying depending on the material being processed, number of pellet layers, and other factors. During this time, 90 to 95 per cent of the iron oxide is converted to DRI. This product is continuously discharged from the furnace at around 1000°C either into refractory-lined cans for hot transfer to the meltshop or into briquetting machines for production of hot briquetted iron (HBI).

Figure 5.8 Fastmet Process Flowsheet



5.2.4 INMETCO® RHF Process

5.2.4.1 Background

Technology developed at Inco Research and Development to recycle metal units from steel mill waste has led to the INMETCO® process, a **coal-based, rotary hearth direct reduction process.**

A 60 000 tpy plant was built by The International Metals Reclamation Co. Inc. (INMETCO), an Inco subsidiary, in 1978, at Ellwood City, Pennsylvania to recycle speciality steel wastes. Mannesman Demag Corp., in association with Inco, used the Ellwood City facility to prove the viability of the process as applied to virgin feedstock, i.e. iron ore. The first commercial, iron ore based INMETCO facility, a 0,3m tpy module and associated iron ore pelletising plant is presently under construction at Nakornthai Strip Mill Co. in Chon-Buri, Thailand. The DRI there will be hot charged to the meltshops.

5.2.4.2 Raw materials

The Inmetco RHF process permits the use of **almost any solid reducing agent,** from **coke breeze** through nearly **all types of carbon to petroleum coke** according to Demag (Nurse [70]). It claims that due to short retention times, the highest level of productivity can be attained for the lowest investment cost of any well-known DR process. The use of direct hot-charging to the electric furnaces also minimises energy consumption.

5.2.4.3 Operating procedure

The INMETCO iron ore direct reduction process involves the mixing and pelletising (6 -12 mm) of dry, finely ground (less than 250 microns) **iron ore** (magnetite or hematite), **reductant** (fine coal, coke or char with less than 25 per cent volatiles), **flux and a binder** (usually bentonite) . The soft, unfired pellets are then conveyed onto a rotary hearth furnace and form a bed of about 20 mm deep. Coal or natural gas fired burners at the edge and, in some designs, the roof of the continually rotating hearth, heat pellets to 1250-1300°C at atmospheric pressure. The configuration of the burners is such that it forms a heating and reduction zone with the former comprising one-third of the hearth, and the latter the rest.

- In the **heating zone**, any volatiles contained in the reductant are released and burned providing heat and the pellets are heated by radiation from the gas and the walls of the furnace. Combustion off-gases flow in the opposite direction to the hearth's rotation and the carbon monoxide formed in the reduction zone is combusted in the heating zone. Heated pellets are rotated into the reduction zone where the carbon in the pellet reacts with oxygen to form carbon monoxide.
- A reducing atmosphere in the **reducing zone** is ensured by operating the burners with a deficiency of air. Pellets are reduced by carbon monoxide to a metallisation of 80-92 per cent, depending upon the time of residence in the furnace (usually 15-20 minutes). Thermal reactions occur rapidly as the pellet bed is brought to temperature without the gas diffusion time necessary in other processes. This means that reactions can occur very quickly with high thermal and chemical efficiencies leading to low retention times. Pellets can be discharged hot (about 850°C) directly into a steelmaking vessel, or cooled and shipped as cold DRI.

Off-gases leaving the furnace at about 1100°C are cycled through a heat exchanger to pre-heat combustion gasses and then after cooling are cleaned in a scrubber and released to the atmosphere. The carbon content of the DRI can be adjusted between 1,5 and 7,0 per cent by varying the carbon addition to the pellets.

5.2.5 Hytemp System

5.2.5.1. Background

The use of DRI has traditionally been criticised as having a higher energy consumption than scrap because of the gangue content and the need to reduce remaining iron oxides. This additional energy can however, be compensated for by the use of hot high carbon DRI such as with the Hytemp technology (Yañez and Alvarez [102]).

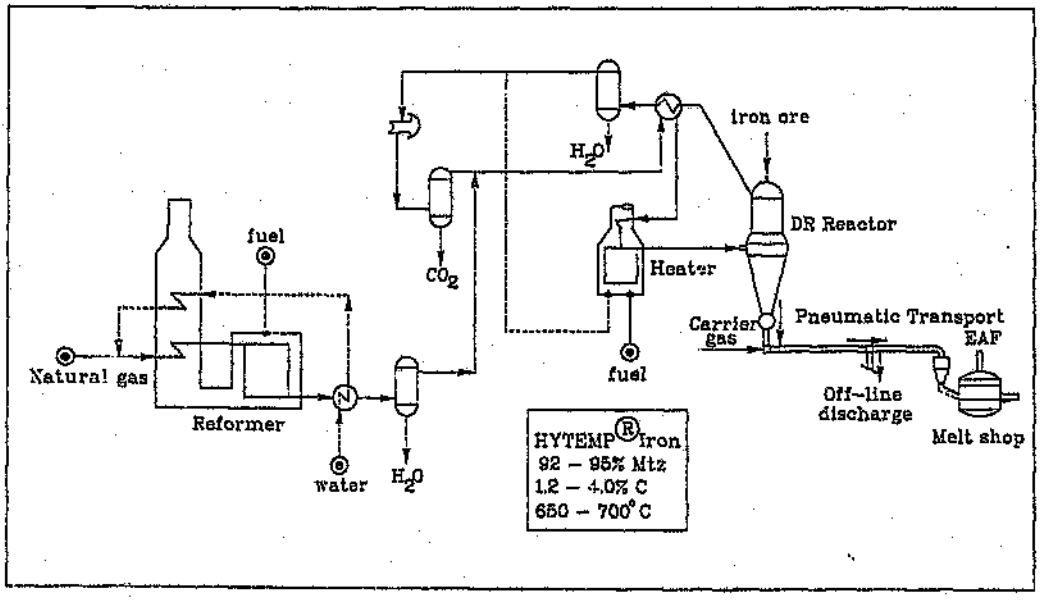
The Hytemp technology was developed by Hylsa, based in Monterrey, Mexico, as a modification of the HYLIII process. The aim was to transfer hot direct reduced iron from the DR reactor to an EAF in a closed pneumatic transport system to take advantage of the sensible heat in the transported material (Duarte [27]). The resultant product is a high-carbon DRI, similar to iron carbide, containing 2 per cent or more carbon rather than the 2 per cent typical of other HYL reactors. HYLSA has

also developed another alternative known as high carbon Hytemp iron, with carbon levels of over 4 per cent, presenting important energy advantages during melting (Yañez and Alvarez [102]).

5.2.5.2 Process improvements

Traditionally, DRI has been discharged cold (50°C) from the reducing reactor (Huskonen [46]). Hot discharge has been in use for a number of years for the purpose of producing briquettes. Although formed hot, briquettes then are cooled for storage, shipment, or later use in electric furnaces.

Figure 5.9 Hytemp System Flowsheet



Research conducted by HYLSA over several years aimed at finding ways of taking advantage of the sensible heat, which is normally removed in the DR reactors' cooling circuit or during HBI cooling. The following concepts where considered:

- heat energy otherwise lost when DRI is cooled could be used in the EAF if the DRI is charged while still hot,
- direct linking of the DR reactor and the EAF would be necessary in order to charge hot DRI - transfer of hot material via buckets or rail cars were ruled out because significant amounts of heat are lost in the transfer process,
- it was decided that the system should be based on pneumatic transport of DRI in a sealed system,
- a feeding device would be required to charge hot DRI and fines to the EAF

5.2.5.3 Benefits of Hytemp

The use of the HYL Hytemp System has virtually no effect on direct reduction process, but benefits start when material exits the reactor outlet and continue onwards to the electric furnace.

Duarte [27] states that savings in the EAF by using 60 percent charge of high-carbon (4 percent) Hytemp iron represents about 115 kWh/t liquid steel when compared with 100 percent use of scrap grade HMS 1. The related increase in productivity is around 22 per cent.

Huskonen [45] explains that since the hot DRI handling is carried out in enclosed systems, the environmental impact is reduced and the total metallic yield is improved due to reduced loss of fines. Once the iron ore is loaded to the top of the reducing reactor, it remains unexposed until it is tapped from the electric furnace as raw steel. By taking advantage of the high temperature of the DRI, there is a reduction of about 19 per cent in electric energy consumption required per ton of liquid steel in the EAF. Productivity, measured in terms of tap-to-tap time, is improved by 16 per cent as well.

The process, which has been tested in a pilot plant for some years, will soon be commercially employed in Hylsa's new 0,6m tpy HYL III module under current construction at its steelworks at Monterrey, Mexico.

5.2.6 Arex-SBD™

5.2.6.1 Background

C.V.G. Siderurgica del Orinoco C.A. (Sidor), is a Venezuelan state-owned EAF-based integrated steelmaker. This company, which will be privatised soon, has a total of eight DRI modules of which four are Midrex 400 modules and another four are HYL I modules. The Midrex modules have been retrofitted with Sidor's **AREX-SBD™** technology which uses an "in situ" or "auto-reforming" principal and does not require a separate gas reformer, but instead, continues to use their separate reformers. Sidor has been operating a "reformerless" AREX pilot plant since the end of the 80's and has formed a company, AREX Technology S.A., to market the process.

Sidor has reported to have reached an agreement for the financing of the first commercial scale stand-alone AREX plant aiming at 450 000 tpy production at a location in Venezuela.

5.2.6.2 Operating procedure

In a pro-forma "stand alone" AREX module, lump or pellets are fed into the top of a vertical furnace, and are continuously heated and reduced by rising gases. Isenberg-O'Loughlin [46] explains that reducing gas is generated from a mixture of dewatered and scrubbed natural gas and recycled top gas. All reduction, reforming and carburising takes place in one vessel, as there is no separate gas reformer. The

mixture of virgin- and top-gas is compressed and preheated, and then mixed with air in a combustion chamber for partial oxidization of methane and to raise the gas temperature to 1100°C to promote reforming. Afterwards, it is injected into the reactor where the metallic iron acts as a catalyst for the reforming reactions, producing a reducing gas that contains more than 85 per cent H_2 and CO. The temperature of the reducing gas is sufficiently lowered to allow the reducing reaction to take place due to the endothermic nature of the reaction

5.2.7 Finmet Process

5.2.7.1 Background

The Finmet Process is a relatively new **fines based fluid bed DR process.** The process came as a revitalisation of the old FIOR technology which has been going through a slow start since its inception some twenty years ago. The FIOR process, which is the only gas-based direct reduction technology relying on ferrous fines as feedstock, has been used at the only operating plant of the kind at Puerto Ordaz in Venezuela. Over most of its lifetime, however, it has been plagued by process and equipment problems. Recently the problems were related to plant availability due to cyclone fouling, which restricted overall output. Energy consumption levels have also been excessive.

Fior decided to reassess its process to lower energy and manpower inputs, seeing that these criteria where not as important when the plant was designed 20 years ago, as they were today. It was thus decided to proceed with the development of an improved fluid-bed process using the know-how developed in the plant, coupled with energy consumption and manpower requirements similar to those of other DR processes. HBI was expected to be produced more cheaply by the use of lower cost iron ore fines.

5.2.7.2 The Improved process

Hassan and Whipp [39] indicate that all of the above--mentioned concerns led, after extensive pilot plant, hot lab and computer simulation tests, to the development of the new improved Finmet process.

The design philosophy for the new plant was to provide two 500 000t/y reactor modules, using common facilities for other functions. The plant was built in an area adjacent to the existing FIOR plant at a cost of $225 million, and started-up at the end of 1996.

The major changes to the process are:

- Elimination of the pre-heat reactor using natural gas to pre-heat iron ore, and instead, providing heat by the off-gas from the reducing reactors. This also eliminates a large air compressor and flue gas scrubber, lowering energy consumption and investment cost.

- The CO_2 removal system can scrub both recycled gas, as well as reformed gas, whereas in the FIOR plant only reformed gas is scrubbed, limiting the amount of CO available to be used in the reducing gas.
- Due to the modification to the reactor design, fines entrainment to the reactor internal cyclones will be reduced. The fines level carried into the cyclone by the gas was reduced by 80 per cent during pilot tests, which will extend cyclone operating time, which was a limiting factor previously.
- Improvements to the cyclone design will also decrease fouling of the cyclone, extending its life.

5.2.7.3 Operating procedure

The reduction process takes place in **4 pressurised fluid bed reactors** set in series at descending heights. Iron ore fines are fed into the highest reactor and flow in succession to the lower ones becoming more metallised at each step. The reducing gas first enters the lowest reactor and is passed to the higher beds, becoming more spent with each step.

The iron ore fines are held in suspension in the fluid bed by the **upflowing current of reducing gas** and act like a bubbling fluid, overflowing by gravity from the higher to the lower reactors. Apparently, the use of bubbling fluid beds allow the process to accept a wide range of particle sizes. Operating temperatures of reactors vary from 550°C in the upper reactor to 800°C in the lower one. Operating pressure is about 10 atmospheres. The metallised fines are discharged at about 740°C before briquetting.

The top gas from the highest reactor is quenched and scrubbed for dust and a small amount of gas is removed to control inert build-up and to serve as fuel gas. The remaining recycle gas is then compressed, mixed with virgin reducing gas from the reformer, passed through CO_2 and H_2S removal units, heated to 875°C and injected into the lowest reducing reactor. The reformer is a conventional steam unit.

5.2.7.4 Benefits of Finmet process

According to Hassan and Whipp [39] natural gas and electrical consumption will decrease in the new process due to:

- Elimination of the ore pre-heater fired with natural gas.
- Higher efficiency reformer with lower steam to carbon ratios.
- Production of inert gas from combustion gas of reformer, instead of burning natural gas.
- Elimination of previously used steam boilers utilised for back-up turbine drivers.

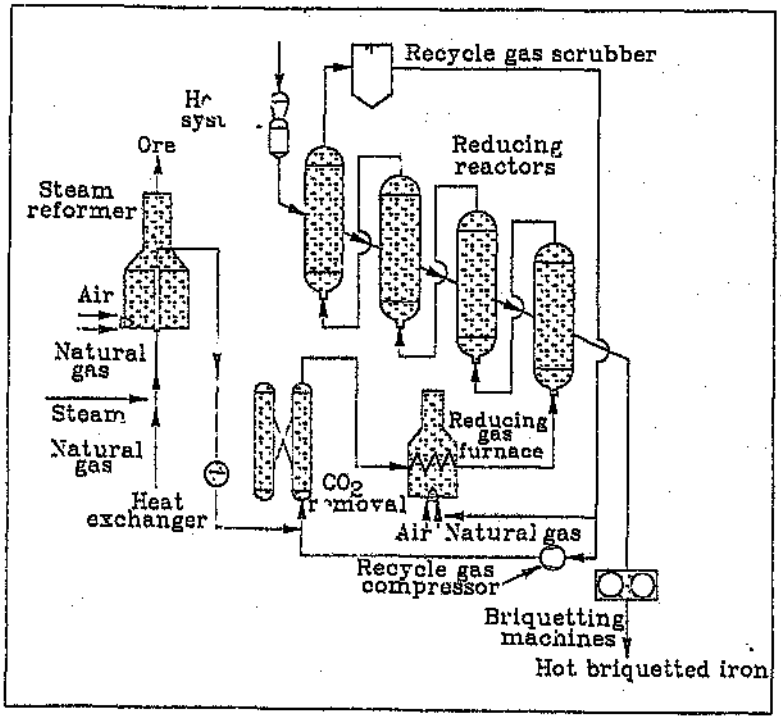
Other unit consumption improvements can be seen in figure 5.7

Table 5.7 Finmet - unit consumption improvements

	FIOR plant	New Finmet process
Ore	2.0 mt/mt	1.6 mt/mt
Natural gas	5.0 gcal/mt	3.0 gcal/mt
Electricity	250 kWh/mt	150 kWh/mt
Water	7.5 m^3/mt	2.5 m^3/mt
Manpower	1.25 mh/mt	0.50 mh/mt

Voest Alpine Industieanlangenbaan (VAI) continues working on developing a related **Finex process.** The process uses fines but is coal-based.

Figure 5.10 Finmet Process Flowsheet



5.2.8 Circored® Process

5.2.8.1 Background

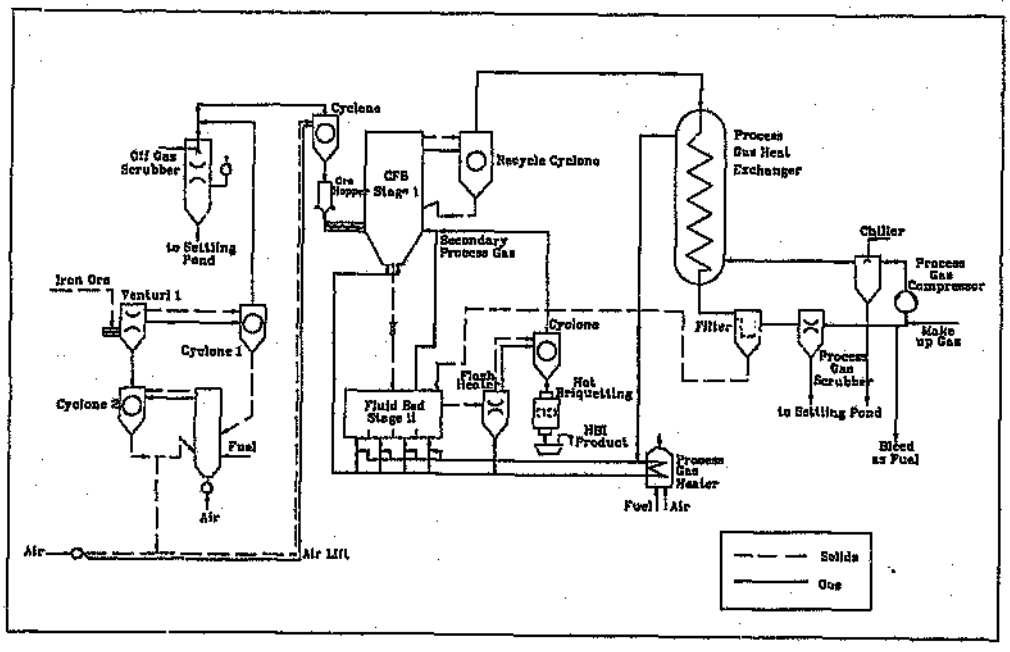
The Circored® Process is a DRI technology developed by Lurgi Metallurgie GmbH of Germany, based on the use of **gas and iron ore fines.** Cliffs & Associates Ltd. have ordered the first commercial 0.5 m tpy Circored plant to be constructed in Trinidad & Tobago.

5.2.8.2 Operating procedure

In the Circored process iron ore fines (0,03-1mm) are dried and pre-heated to about 850°C in a **two stage fluid bed pre-heater** which separates the gas and fines before the ore is fed to a lock hopper system which continuously charges the first stage reactor.

- The **first stage reactor** is a **circulating fluidised bed** where the fluidising gas is a mixture of heated process gas and off-gas from the stage 2 reactor. The process reactions are endothermic, the required energy provided by the pre-heated fines and process gases. Fines forced upwards by the high gas velocity in the reactor are captured by a cyclone before being recirculated to the lower part of the reactor. The off-gas from the recycle cyclone passes through a process gas heat exchanger, a multi-clone for the recovery of very fine dust particles which are then recycled into the last compartment of the second stage reactor and then scrubbed and quenched for the removal of dust and water produced during reduction. Fines which have been reduced to about 70 per cent metallisation are fed to the second stage reactor by a flow regulating control valve near the bottom of the reactor.

Figure 5.11 Circored Process Flowsheet



- The **second stage reactor** is a **fluidised bubbling bed** segregated into four sections. Gas from the heat exchanger and the process gas heater are mixed and fed to each compartment to obtain about 93 per cent metallisation. The "sticking" problem is avoided seeing that the reduction temperature in both reactors is below 650°C. This relatively low operating temperature leads tot specifically high process gas volumes and a relatively high operating pressure of four atmospheres. Fines at 630°C are discharged from the second stage reactor, but need to be further heated to attain a high enough temperature for briquetting.
- These fines pass through a flash heater where they are in contact with hot process gas and are heated to 680°C before being carried to a cyclone. The cyclone separates the heating gas, which it recycles to the stage one reactor, and sends the reduced fines to the briquetting machine.

Plant capacities of between 0,5m and 2,0m tpy are offered in a single strand for the Circored technology.

5.2.9 Circofer® Process

5.2.9.1 Background

The rather new Circofer process developed by **Lurgi Metallurgie** of Frankfurt, Germany combines excellent heat and mass transfer in the **circulating fluidised bed** to convert **iron ore fines and coal** into low cost DRI with no export fuel. The sticking, accretion and reoxidation problems associated with previous processes are avoided by operation with excess carbon and separation of the gasification and reduction zones (Schlebusch et al [13]).

The circulating fluidised bed (CFB) reduction of fine ores has been investigated by Lurgi for more than 20 years and was first put into effect in the form of a pilot plant in Sweden in the ELRED Process from 1976 to 1980 (Bresser and Weber [14]). Further testwork was carried out at the Lurgi Research Centre in Frankfurt in a 700 mm CFB pilot plant in 1984.

In view of accretion problems resulting from the reduction and oxidation taking place in the same reactor, it appeared important to separate the two zones in a modified flowsheet. This led to the development of the present concept of the Circofer Process in 1985, where the **oxidising zone** was **separated from the reduction zone.** This is a developing technology and no commercial plants have been built yet.

5.2.9.2 Feed materials

The Circofer Process possesses the decisive advantage of being able to process **inexpensive fine ores and coal.** The result of this does not only give cost advantages compared to other DR methods, but also ensures versatility with respect to plant location since coal as a primary energy source is globally available. The principal difference between Circofer and its sister process, Circored is that instead of using natural gas as reductant it uses coal (sized under 10mm) and thus the main reductant is carbon monoxide (CO) as opposed to hydrogen (H_2).

The technical criteria required in feed materials are:

Iron ores - the only quality requirement relates to the particle size of the ore. In order to avoid gas velocities needed for fluidisation from being too high, the fine ore should have a size range between 1mm and 0,03 mm.

Coals - the only prerequisite for characteristics of the coal relates to the ash softening temperature which should not be below 1050°C. The Circofer Process allows the use of a wide range of coals with respect to their volatile contents (10-40%); even coals with high volatiles such as lignites.

Depending on the process control and retention time in the reducing unit, a product metallised to about 93 per cent, with char content of about 10-20 per cent is discharged from the reactor.

5.2.9.3 Operating procedure

Fines ores are first pre-heated in a two-stage pre-heating system before being introduced into a two-stage reactor system, with the CFB and FB connected in series (Weber et al [98]). This arrangement allows adaptation of the reactors to correspond to the reaction characteristics of reduction and hence optimise gas utilisation and process control.

Consequently, the initial fast reaction step of pre-reduction of up to about 70 per cent metallisation, essentially with high specific mass transfer, is accomplished in the CFB reactor with short retention time and optimum gas utilisation. The final reduction to a level of metallisation of plus 92 per cent is accomplished in the second stage FB reactor with longer retention times.

According to Weber et al [98], one of the major features of the Circofer Process is the separation of the coal gasification stage from the actual reduction of the ore in the reduction reactor. While the energy necessary for the endothermic reduction reaction is generated in the gasifier, the reduction of the fine ores is accomplished in a two stage CFB/FB (Circulating Fluidised Bed/Fluidised Bed) reactor system.

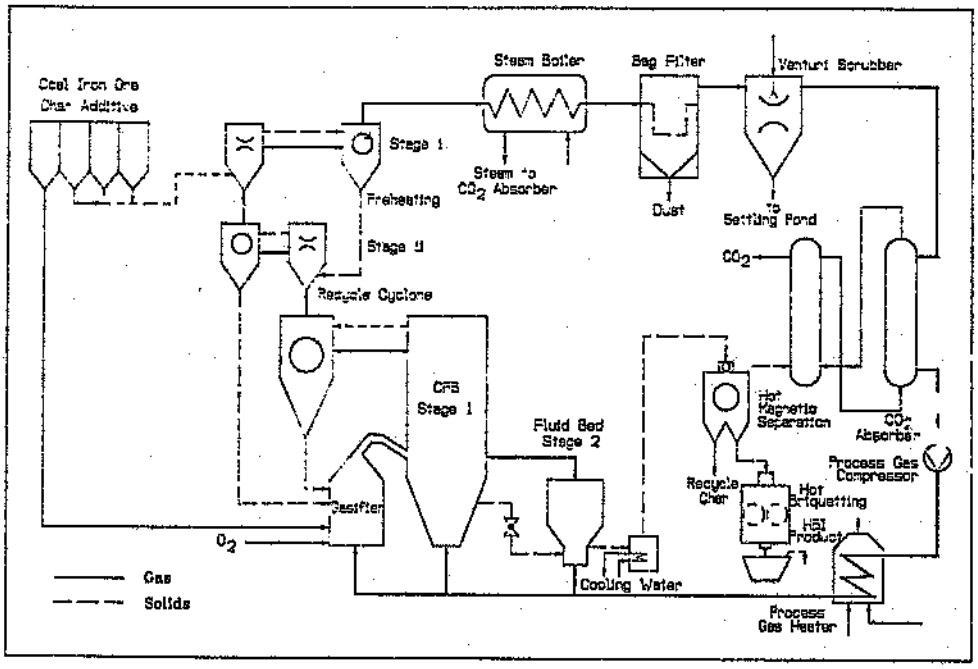
5.2.9.4 Benefits of CFB technology

Other advantages of using CFB technology include:

- avoidance of any surplus export gas production due to a high gas conversion rate,
- prevention of sticking by utilising a high amount of excess carbon as well as high kinetic energy of particles due to high gas velocities,
- high temperature operation (around 950°C) without accretion and sticking phenomena,
- gas velocities of 5 to 6 m/s lead to smaller reactor dimensions.

Plant capacities of between 0,5 and 2,0m tpy in a single strand are offered by Lurgi using Circofer technology

Figure 5.12 Circofer Process Flowsheet



5.2.10 Iron Carbide

5.2.10.1 Background

The ICH™ iron carbide process was developed by Hazen Research Inc and is now owned and merchandised by Iron Carbide Holdings Inc. (ICH™).

The first commercial Iron Carbide plant was built for Nucor in Trinidad & Tobago in 1994. This 0,3m tpy facility had an output of less than 50 per cent of nominal capacity, but showed improvements later on. A second Iron Carbide facility, with capacity of 0,66m toy is being constructed by Qualitech in Texas.

The principle behind this technology is similar to some other gas and fines based DRI processes in that it relies on **fluidised bed technology.** The aim of the process is to produce a near-pure iron carbide fines product (Fe_3C) containing carbon and iron as compounds explain Nucor's Iverson [47]. The resulting product is stable, and not pyrophoric, with total carbon content of 6 per cent, which is significantly higher than other DRI products, although some technologies can offer high carbon options raising the carbon content up to 4 per cent (mostly Fe_3C). Carbon in excess of that

needed to reduce any remaining iron oxide can be used to supply energy in EAF steelmaking, increasing the productivity of the furnace. In BOF steelmaking, carbon can reduce remaining oxides in the hot metal charge.

A lot of interest is currently shown in the field of Iron Carbide, mostly due to the high fuel value of carbide's 6 per cent carbon content. Some steelmakers have problems with the economics of high-carbon iron in that the higher carbon content displaces iron, and consequently, more high-carbon DRI needs to be charged than if standard DRI was use. Some are of the opinion that the value of the additional iron required is greater than that of the energy saved (Duarte [27]).

The interest shown by steelmakers for iron carbide are not just for the electrical energy content but iron carbide, being a naturally stable compound, can be produced in fine particles without the danger of re-oxidisation. This facilitates continuous steelmaking and metering of the charge (McManus [59]).

5.2.10.2 Operating procedure

In this process, iron ore fines (0,1-1 mm) are reduced and carburised with a stream of methane and hydrogen rich gas in a single stage fluidised bed reactor. Iron ore fines are pre-heated and pressurised to 4 atmospheres in lockhoppers before being fed to the fluid-bed of the reactor which is at 600°C (Stephens [93]).

Low reaction temperatures promote the formation of Fe_3C and also avoid the sticking problem associated with the higher operating temperatures of other competing process. The basic process equation is:

- $3Fe_2O_3 + 2CH_4 + 5H_2 \Rightarrow 2Fe_3C + 9H_2O$

Residence time in the reactor is about 16 hours, after which the iron carbide passes through a sealed product cooler and is discharged at about 60°C.

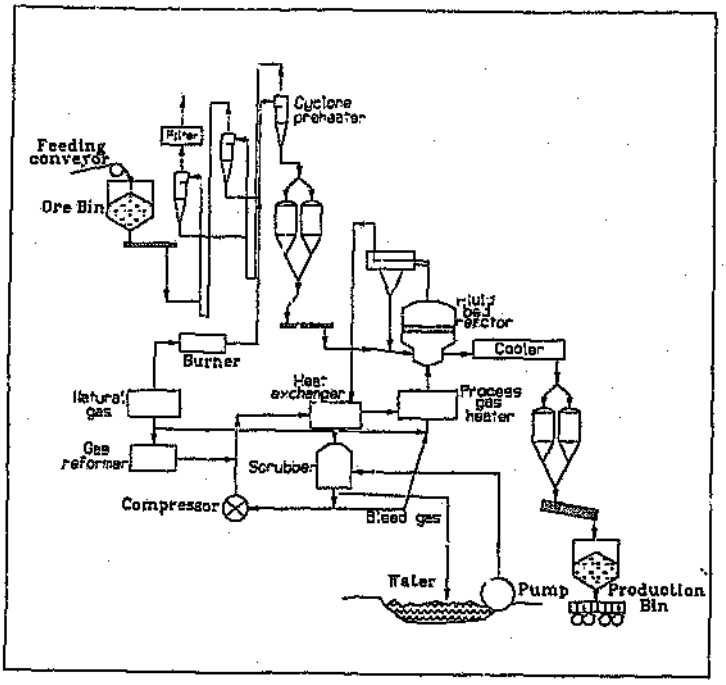
Fines contained in the top-gas are removed by passing through a cyclone before returning to the reactor. Top- gas then passes through a heat exchanger where it is cooled by indirect contact with colder reducing gas and then passes into a scrubber to remove dust and water. After some gas is bled off to control the nitrogen content, the remaining recycle gas is combined with hydrogen from a steam reformer and methane. The combined gas stream is first heated in the top-gas heat exchanger, then reheated to 725°C in a gas fired heater before being introduced into the bottom of the reactor again.

5.2.10.3 Benefits of Iron Carbide

According to Stephens [93] the benefits of the process are:

- the use of iron ore fines or concentrates, which are less expensive than pellets commonly used in other DR processes,
- no sticking or defluidisation of the metal in reactors due to low operating temperatures,
- non-pyrophoric nature - does not need to be briquetted at extra cost

Figure 5.13 Iron Carbide Process Flowsheet



5.2.11 GHAEM Process

5.2.11.1 Background

The GHAEM process, developed by National Iranian Steel Co. (Nisco), is a **gas-based technology** using **iron ore lump and pellets** as feedstock. The only GHAEM DRI facility which is currently in commercial operation is 0,6m tpy plant operated by Esfahan Steel Co. (ESCO) in Esfahan, Iran which commenced operations in 1996, with product mostly destined for the domestic market.

5.2.11.2 Operating procedure

The GHAEM process is similar to the major gas and pellet based DRI technologies in that it utilises a continuous process shaft furnace with reduction and cooling zones. This process can make use of 100 per cent pellets, but trials with a mixture of 80/20 pellet/lump charge have also been used successfully.

The principal difference is that the reducing gas in the GHAEM process is not produced by cracking of natural gas in the presence of a catalyst in a reformer, but is formed by the partial oxidation of natural gas in a combustion chamber ($2CH_4 + O_2 \Rightarrow 2CO + 4H_2$).

The process, which generates reforming gases in the shaft furnace rather than a separate unit, is acclaimed to have capital costs only half that of a comparable

Midrex or HYL unit. Also, it shows higher metallisation, is less susceptible to reoxidation, lowers electricity and fuel consumption compared to Midrex, and has much lower operating costs.

5.2.12 Corex ironmaking and DRI

5.2.12.1 Background

Corex is a direct smelting reduction process for the production of hot metal from coal and iron ore. The process, although not strictly a direct reduction process, is of interest in that it produces top gas which can be combined with a direct reduction facility to produce DRI as a by-product.

South Africa was the leader in effectively constructing and utilising the Corex iron making process for the first time. The KR process or Corex is derived from its German name of 'Kohle Reduktion' and uses the same raw materials as the coke oven and blast furnace route, but almost any non-coking coal can be utilised. South Africa's limited reserves of coking coals sparked the move towards a new liquid iron production process.

5.2.12.2 Corex process

Bohm et al [10] explain that lump ore sinter, pellets, or a mixture of these, are charged into the reduction shaft and reduced to a product of around 90 per cent metallisation by means of counterflow. This product is then conveyed into a melter gasifier by discharge screws, where final reduction and melting occur before the necessary metallurgical metal and slag reactions take place. Hot metal and slag tapping then takes place similar to that of the blast furnace.

This process of smelter reduction, however, renders top-gas as a ...roduct, which is cleaned and cooled in a scrubber and can be used in, or sold, for application in, power generation plants, chemical plants, iron and steel plant but more importantly, for the production of DRI.

5.2.12.3 DRI production using Corex export gas

The reducing gas generated by the Corex process needs to be sent to a CO_2 removal system incorporating processes such as Pressure Swing Adsorption (PSA) and other chemical processes, before being used in the reduction shaft for the reduction of the iron ore.

The reducing gas leaving the CO_2 removal system has to be heated in order to achieve the optimum reducing temperature in the reduction shaft. The gas has to be heated to 850°C, which is the most suitable reducing temperature, in a very short time to prevent the generation of elementary carbon. This is achieved by burning a small quantity of the reducing gas with oxygen and injecting it into the main gas chamber and into a combustion chamber, increasing the temperature to the desired level.

Heated reducing gas enters the reduction shaft at the bottom of the reduction zone and proceed upwards through the descending bed of oxide material, charged in the upper part, reducing it as it goes upwards. Reduced iron ore descends to the lower part at the bottom of the shaft, where it is continuously discharged

Top gas which leaves the reduction shaft after reduction, still contains additional CO_2 and H_2O which needs to be eliminated through scrubbers before being recycled and used as reducing agent again.

Material could now be discharged hot, in the case where the reduced iron is used in an adjacent steel plant, or put through a process of hot or cold briquetting, if the reduced iron is intended to be sold as a merchant product.

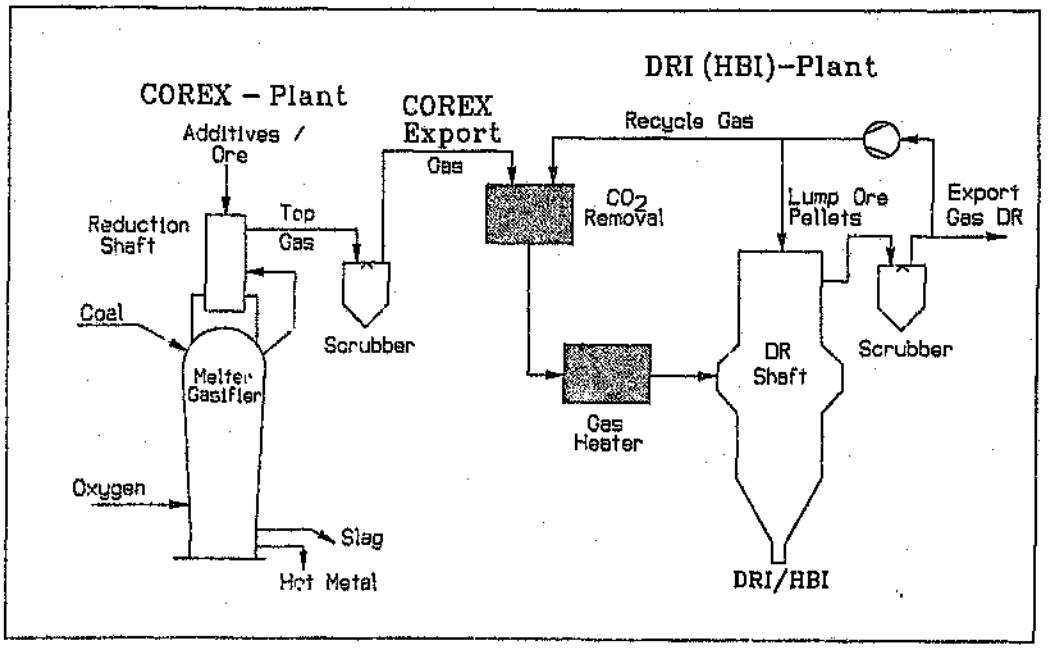
With the top gas created in hot metal production via the Corex route, 1,2t of DRI can be produced per ton of hot metal, or up to 1,3t DRI if the coal input into the COREX melter gasifier is increased.

5.2.12.4. Benefits in using Corex off-gas for DRI production

Bohm et al [10] state that production cost advantages in using this route of steelmaking are:

- the use of Corex hot metal and DRI/HBI,
- production of hot metal equal to blast furnace quality,
- the use of low cost raw materials such as non-coking coal and lump ore,
- the use of Corex gas as reducing agent for DRI/HBI production,
- using the EAF as the steelmaking process with high hot metal input.

Figure 5.14 Corex/ DRI Process Flowsheet



CHAPTER 6 DIRECT REDUCED IRON - LOCATION & CAPACITY

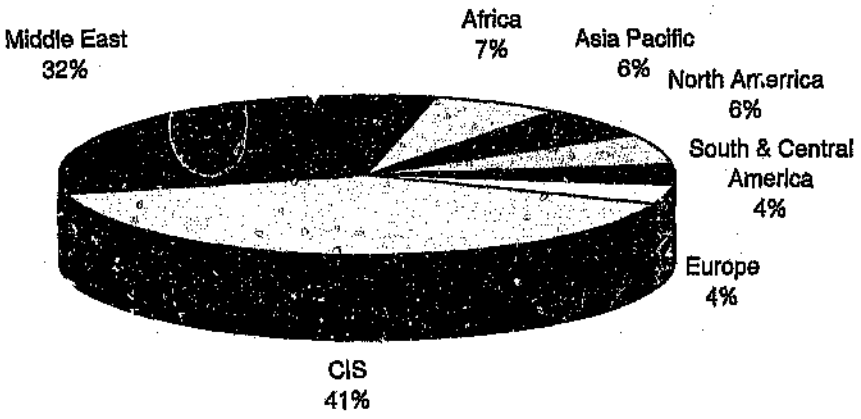
6.1 Location of raw materials

The most critical factor influencing the location of DRI plants is the availability of raw materials. Therefore, DRI facilities tend to be concentrated in areas with abundant iron ore, natural gas or coal supplies.

6.1.1 Location of global natural-gas reserves

Although world oil reserves are mainly concentrated in OPEC-controlled countries, the distribution of natural gas reserves, used by direct reduction plants, are concentrated somewhat differently (figure 6.1).

Figure 6.1 Global distribution of gas reserves, 1996



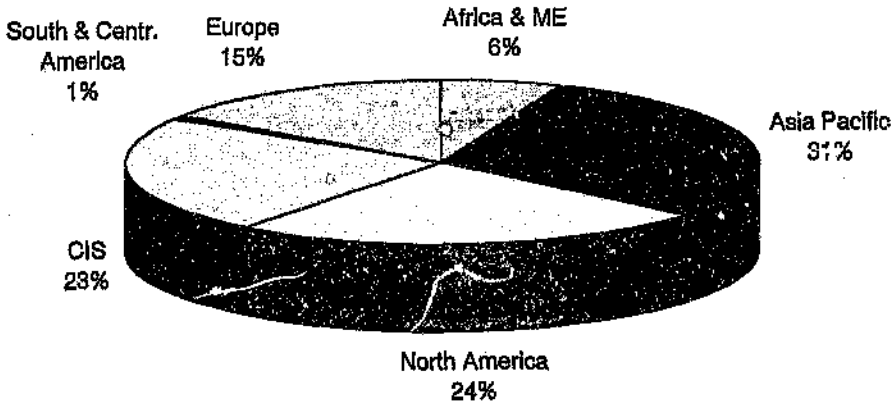
Natural gas reserves are most abundant in the former soviet union countries (CIS), and Iran. The areas in which DRI capacity is the greatest are those where natural gas is abundant and priced accordingly: Venezuela, the Middle East and Russia.

North America also has vast quantities of natural gas reserves, but they may be three to four times the price of the Venezuelan or Trinidadian gas. This has been a limiting factor to growth of a reduced iron industry in North America, where numerous first-generation reduction plants were built during the late 1960's and early 1970's until the first major oil crisis struck. Currently only two plants are operating (see table 6.2).

6.1.2 Location of global coal reserves

The USA is a prime site to develop a coal-based DR industry. Existing domestic oil and natural gas reserves in the USA could be expected to be depleted by 2050, but they still have several hundred years supply of coal, exceeding the entire world's proven natural gas reserves in terms of equivalent barrels of oil (figure 6.2).

Figure 6.2 Global distribution of coal reserves, 1996



India, China and South Africa also have vast reserves of hard coal.

6.1.3 Location of global iron ore reserves

The former USSR has large iron ore reserves, but they are of a low grade. The high tonnages of Chinese iron ore production are also of low grade. Australia has big deposits and is mining large parts of it.

Due to deregulation of the Australian gas industry and a consequent lowering of gas prices, this country is embarking on large scale value-adding to their iron ore through DRI. Brazil has the world's largest iron ore exporting company, CVRD, and contributes a large part of world high grade iron ore supply (table 6.1).

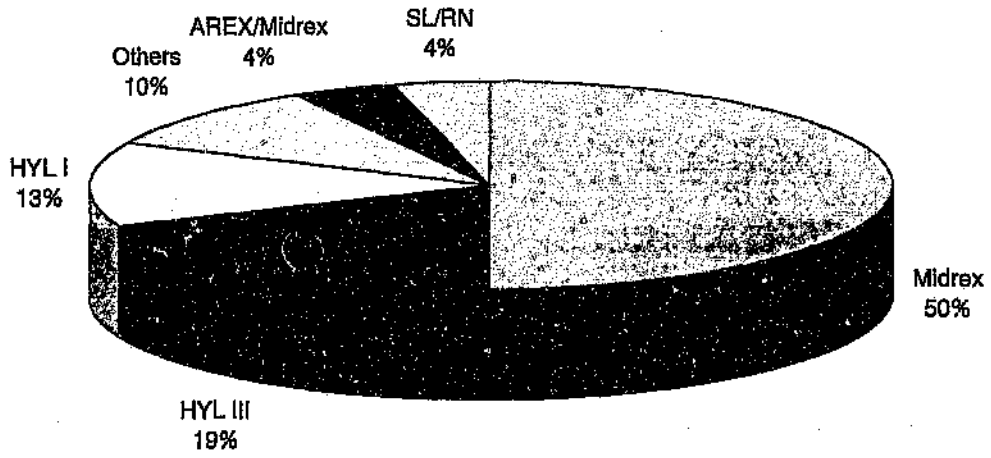
Table 6.1 - World iron ore reserves and production, 1996

	Reserves		*Production*	
COUNTRY	*Mt*	*%*	*kt*	*%*
CIS	29 000	28	129	12,8
Australia	18 000	17	147	14,5
Canada	10 000	10	37	3,7
China	10 000	10	246	24,3
Brazil	10 000	10	180	17,8
India	6 300	6	67	6,6
USA	6 000	6	62	6,1
South Africa	5 900	6	31	3,1
Sweden	2 400	2	21	2,1
Venezuela	1 700	2	19	1,9
Other	4 600	4	72	7,1
Total	103 900	100	1011	100

6.2 Current DRI capacity

6.2.1. Technology - Current global nominal capacity is about 37,5m tpy. By far the majority (90%) of this is gas-based with the two dominant technologies being Midrex (55%) and HYL (32%) (figure 6.3). Feedstock in most cases is lumpy iron ore and pellets. Exceptions to these are Nucor's iron carbide plant in Trinidad, and the FIOR plant in Venezuela which use iron ore fines. The rest (10%) of the capacity is based on coal and other solid fuels. Contrary to the gas-based units with large output capacities of over 1 million tpy, the coal-based units have traditionally much lower output capacities (0,2-0,6 Mt/y).

Figure 6.3 Percentage distribution of DRI technologies - 1996



6.2.2. Regional - The global distribution of DRI capacity is mostly concentrated in poor countries. These are normally captive to nearby steelworks which use most of the produce. In some cases excess produce is sold on the open market. The following tables show the existing DRI capacities in various regions.

6.2.2.1

Table 6.2 - Existing DRI capacity - North America

Region/ Company	Nominal Capacity (million tpy)	Location	Technology
North America	5.1		
Hylsa SA de C.V.	1.4	Monterrey, Mex. Puebla, Mex.	HYL III
Ispat Mexicana S.A. de C.V (IMEXSA)	2.0	Lázaro Cárdenas, Mex.	HYL III
Tubos de Acero de Mexico S.A. (TAMSA)	0.3		HYL I
Sidbec Dosco Inc.	0.4 + 0.6	Quebec, Canada	Midrex
Georgetown Steel Corp. (GSC)	0.4	South Carolina, USA	Midrex

6.2.2.2

Table 6.3 - Existing DRI capacity - South America & Trinidad

Region/ Company	Nominal Capacity (million tpy)	Location	Technology
South America & Trinidad	8.2		
C.V.G Siderurgica del Orinoco C.A. (Sidor)	3.7	Venezuela	2 x HYL I 2 x Midrex (AREX)
Operaciones al Sur del Orinoco C.A. (OPCO)	0.85	Puerto Ordaz, Venez.	Midrex
Venprecar	0.66	Puerto Ordaz, Venez.	Midrex
Flor de Venezuela S.A.	0.4	Puerto Ordaz, Venez.	FIOR
Caribbean Ispat Ltd. (CIL)	2 x 0.42	Port Lisas, Trinidad	Midrex
Acindar Industria Argentina de Aceros S.A.	0.6	Villa Constitucion, Argentina	Midrex
Siderca S.A.I.C.	0.4	Argentina	Midrex
Usina Siderurgica de Bahia S.A. (Usiba)	0.3	Salvador, Bahia, Brazil	HYL III
Other	0.2	Brazil & Peru	SL/RN

6.2.2.3

Table 6.4 - Existing DRI capacity - Asia

Region/ Company	Nominal Capacity (million tpy)	Location	Technology
Asia	10		
India	5.1		
-Essar Gujarat Ltd.	3 x 0.44	Hazira	Midrex
-Ispat Industries Ltd.	1.0	Salvi, Raigad	Midrex
-Grasim Industries Ltd.	0.75	Raigad	HYL III
-Other	2.1	central, eastern, southern regions	coal based rotary kilns
Indonesia	3.0		
-PT Krakatau Steel Co. (PTKS)	2 x 0.68 3 x 0.56	Western Java	HYL III HYL I
Malaysia	1.85		
Perwaja Steel Sdn Bhd (PSSB)	2 x 0.6	Kemaman	HYL III
-Amsteel Mills Sdn. Bhd.	0.65	Labuan Island	Midrex 600

6.2.2.4

Table 6.5 - Existing DRI capacity - Middle East

Region/ Company	Nominal Capacity (million tpy)	Location	Technology
Middle East	8.2		
Iran	6.4		
National Iranian Steel Co. (NISCO)	6.4		
-Khuzestan Steel Co.	2.6	Ahwaz	Midrex (1.3m tpy) HYL (1m tpy) Purofer (0.3m tpy)
-Mobarekeh Steel Co.	3.2	Esfahan	Midrex
-Esfahan Steel Co. (ESCO)	0.6	Esfahan	Purofer
Saudi Arabia	1.5		
Saudi Iron & Steel Co. Ltd. (Hadeed)	0.4 0.65	Al Jubail	Midrex
Qatar	0.4		
Quatar Steel Co. Ltd.	0.4	Umm Said	Midrex

6.2.2.5

Table 6.6 - Existing DRI capacity - Africa

Region/ Company	Nominal Capacity (million tpy)	Location	Technology
Africa	4		
South Africa	1.1		
-Iscor Ltd.	4 x 0.18	Vanderbijlpark	SL/RN
	0.15	Dunswart, Benoni	CODIR
-Scaw Metals (AAC)	0.18	Germiston	DRC
-Davsteel	0.04		
Egypt	0.72		
Alexandria National Iron & Steel Co. (ANSDK)	0.72	El-Dikheila	Midrex
Libya	1.1		
Libyan Iron & Steel Co. (LISCO)	2 x 0.55	Misurata	Midrex
Nigeria	1.0		
Delta Steel Co.Ltd. (DSC)	2 x 0.51	Warri	Midrex

6.2.2.6

Table 6.7 - Existing DRI capacity - Europe & CIS

Region/ Company	Nominal Capacity (million tpy)	Location	Technology
Western Europe			
Hamburger Stahwerke GmbH	0.4	Hamburg	Midrex
CIS			
Oskolskiy Elektrometallurgicheskiy Kombinat (OEMK)	4 x 0.42	Stary Oskol, Russia	Midrex

The production of DRI/HBI in Europe has many difficulties:

- There is a **limit availability** of local **high grade ore**, except Sweden and Russia, otherwise it is necessary to import high grade ores or pellets, which is relatively easy at least in a number of coastal sites (Astier[3]).
- The **cost of natural gas** is generally high
- The **cost of manpower** is high.

This situation could change if coal-based processes are developed or if the gas prices become more attractive.

6.3 Future DRI capacity

6.3.1 New projects

Looking at all the new DRI projects which came on stream in the past few years, together with those planned in the future up to the turn of the century, it is clear that there has been a virtual explosion of **new DRI projects** world-wide in recent years (see table). Currently, there are nearly 20m tpy additional capacity under construction, with at least 48m tpy being under consideration. Including the phenomenon of capacity creep, a total of 115m tpy of capacity could be added by the year 2005.

Compared to only 10 per cent merchant capacity of existing plants, 50 per cent of capacity under construction and 80 per cent of that under consideration will be targeted at the merchant market. These merchant DRI producers are not restricted to poor countries, as was the case with the captive plants, but rather the determinants in consideration of a suitable location are the availability of low cost iron ore, gas and proximity to consumer markets.

Table 6.8 Current and future DRI projects world-wide

Company/works	Capacity ('000tpy)	Process	Fuel	Status	Start(ed) up
AUSTRALIA					
AUSI, Cape Lambert	3,600	HYLIII	Gas	Under development	2000
BHP, Port Hedland	2,500	Finmet	Gas	Under construction	1998
Kingstream, Narngulu	2,400	HYLIII	Gas	Under construction	2000
BAHRAIN					
NDIL	1,200	Midrex	Gas	Proposed	2000
EGYPT					
ANSDK II, El Dikhella	800	Midrex	Gas	Operating	1997
INDIA					
JSIL II, Chandil	150	SL/RN	Coal	Under construction	1998
Ipitata, Joda	120	Tisco	Coal	Under construction	1998
Jindal Strips, Raigarn	200	Jindal	Coal	Under construction	1998
Monnet Ispat, Raipur	100	Jindal	Coal	Under construction	1998
Prakash Industries II	150	SL/RN	Coal	Under construction	1998
IRAN					
Asco, Ahwaz	1,000	HYLIII	Gas	Under construction	1999
Nisco, Esfahan	600	Ghaem	Gas	Operating	1997
MEXICO					
Hylsa, Monterrey (4M)	750	HYLIII/ Hytemp	Gas	Operating	1997
Inmexsa, Lazaro Gardenas	1,200	Midrex	Gas	Operating	1997
Qualitech, Corpus Christi	720	Iron Carbide	Gas	Under construction	late-1998
MOZAMBIQUE					
JCI, Beira	2,500	Finmet	Gas	Proposed	2000+
RUSSIA					
Lebedinsky	900	HYLIII	Gas	Under construction	1998/99
SAUDI ARABIA					
Hadeed, Al-Jubail	1,100	HYLIII	Gas	Under construction	1998
SOUTH AFRICA					
Murray & Roberts, Richards Bay	1,000	Midrex	Gas	Proposed	2000
Saldanha Steel	804	Corex/ Midrex	Gas	Under construction	1998
Scaw Metals	150	DRC	Coal	Operating	1997
THAILAND					
Nakorn Thai, Chonburi	500	Inmetco	Coal	Under construction	1999
TRINIDAD					
Caribbean Ispat, Point Lisas	1,360	Midrex	Gas	Under construction	late-1998
Cliffs Assoc., Point Lisas	500	Circored	Gas	Under construction	mid-1998

Table 6.8 Current and future DRI projects world-wide - Continued

Company/works	Capacity ('000tpy)	Process	Fuel	Status	Start-up
USA					
BS, Mobile, AL	880	Midrex	Gas	Operating	1997
GS/Birmingham S, Convent, LA	1,200	Midrex	Gas	Operating	1997
KM Iron Co., New Orleans, Louisiana	450	Fastmet	Coal	Under development	2000
Tondu & Associates, Louisiana	1,500	HYLIII or Midrex	Gas	Proposed	2000+
VENEZUELA					
Comsigua, Puerto Ordaz	1,000	Midrex	Gas	Under construction	end-1998
Ispat Guayana, Puerto Ordaz	1,200	Midrex	Gas	Under construction	1999
Orinoco Iron, Puerto Ordaz	2,200	Finmet	Gas	Under construction	1999
Posven	1,500	HYLIII	Gas	Under construction	1999

If the projects in the table above all proceed as planned, nearly 20 mt of additional capacity will be added to the existing 37,5 mtpy installed capacity.

6.3.1.1 North America

USA

- Midrex is developing a coal-based **Fastmet process** using fines and a first plant will be built at New Orleans, Louisiana for KM Iron Co., a joint venture between Japanese steelmaker Kobe Steel, which owns Midrex, and trader Mitsui & Co.

- **Two Midrex modules**, installed by British Steel almost 20 years ago in Scotland but never used due to higher than expected costs of gas, were moved to a site at Mobile, Alabama where they were commissioned in late 1997.

- **American Iron Reduction (AIR)**, a joint venture between GS Industries and Birmingham Steel, finished building a **1,2m tpy Midrex Megamod ™ DRI plant** at Convent, Louisiana late in 1997.

- Houston-based industrial project developer, **Tondu Corp.** is sponsoring another DRI project scheduled for Louisiana at a site in St. James parish with a deep-water frontage on the Mississippi River. A choice has to be made between **Midrex or HYL** technologies.

A study done recently by Minnesota Power found that, although most of the new US DRI plants are being built on the Gulf Coast, a gas-based DRI plant situated in the

ore fields of the Great Lakes basin could produce DRI at little more than half the cost of one based on the coast (Nurse [70]).

Mexico

- **Ispat Mexican S.A. de C.V. (INMEXSA)** completed construction on a **1,2m tpy Midrex Megamod™** at Lázaro Cárdenas on the Mexican west coast in 1997.

- **Hylsa SA de CV** finished building a **0,75m tpy HYL III/ Hytemp** unit at its site at Monterey, Mexico - the first time a HYL III furnace were equipped with a **HYTEMP® Pneumatic Transport** system to charge hot DRI to the furnace. (Hassan & Whip [39]).

- Newcomer **Qualitech** is constructing a **0,72m tpy iron carbide plant** at Corpus Christi, in Mexico using fluid bed reactors.

6.3.1.2 South America and Trinidad

Trinidad & Tobago

DRI plants built here seem to be well-placed due to low-cost gas, proximity to iron ore from Brazil and Venezuela, and proximity to the US consumer market. Although lower prices are available at other locations, some producers, like Nucor, concluded that the political stability gave Trinidad the edge (Iverson [47]). Trinidad is beginning to compete with Venezuela as a major supplier of DRI to the USA.

- A joint venture between iron ore miner **Cleveland-Cliffs Inc.**, steelmaker **LTV Corp.** and plantmaker **Lurgi AG** will see the start up of a HBI plant with a 500 000 tpy capacity, rising eventually to 1,5m tpy. This is to be built in Trinidad & Tobago to supply the US market, using Lurgi's gas-based **Circored fluidised bed technology** for the first time. CVRD will supply the fines and the gas will come from The National Gas Co. of Trinidad & Tobago.

- The world's largest **Midrex "Stretch Megamod"** unit , capacity 1,36m tpy, contracted by **Carribean Ispat Ltd. (CIL)** will be built at its Point Lisas steelworks using lump and pellets from Brazil and Venezuela.

Venezuela

This country, which is the largest DRI producer in the world (5,34 mt in 1996), proves to be an ideal site for DRI facilities due to its abundant iron ore supplies and low cost natural gas (Hassan and Whipp [39]). Government owned iron ore supplier, **Ferrominera Orinocco (FMO),** is actively promoting new DR projects, making it one of very few mining companies that is participating in the construction and operation of DR plants.

- An Orinoco Iron project for a 2,2m tpy plant using **Finmet technology** is being constructed by **BHP** and Venezuela's **Sivensa,** situated at Puerto Ordaz, near the mouth of the Orinoco River.
- A 1,5m tpy **Midrex plant** in Venezuela by South Korea's **Pohang Iron & Steel (Posco)** and Venezuelan iron ore miner **CVG** will be commissioned in 1999. The plant **(Posven)** will supply Posco with HBI for a new thin slab mini-mill.

- In another partnership, CVG and Kobe Steel have formed **Comsigua** which will operate a 1m tpy **Midrex Megamod™ plant** currently still under construction in Venezuela.

6.3.1.3 Asia

India

This country is currently the second largest producer of both coal and gas-based DRI in the world with output of some 4,3 mt in 1995. All the new Indian projects which will come on stream in the next few years are **coal-based** and will make use of the large resources of non-coking coals in the country. The largest of the established plants are, however, gas based.

- One of the most recent of the Indian plants started-up in 1996 in the Ghugus by **Lloyds Metals & Engineering** is a **150 000 tpy module** using the **OSIL process.** It is the first time that this coal-based process, which was developed by Orissa Sponge Iron Ltd, is used by anyone other than the company itself. A second module of the same dimensions was added in late 1997.
- Another five small expansions to coal-based technology will see a total of 0,72m tpy addition to India's DRI capacity by the turn of the century.

South Korea

- An 800 000 tpy **Midrex** shaft furnace has been almost completed at Asan Bay, South Korea for **Hanbo Steel & General Construction Co. Ltd.** Hanbo, however, has been declared bankrupt and the plant is currently under management of Posco. After completion under new management in late-1998, the plants will probably be sold to India's Jindal, which has shown interest.

Thailand

- Inmetco, a subsidiary of Canadian nickel producer Inco, has developed a **rotary hearth furnace (RHF)** which produces direct reduced pellets from iron ore and coal charge. Mannesmann Demag is building the first such plant for Thailand's Nakorn Thai Group as part of a 1,5m tpy EAF based flat product steelworks near Bangkok.

6.3.1.4 Middle East

Saudi Arabia

- **Saudi Iron & Steel Co (Hadeed)** is building a **1,1m tpy HBI plant** at Al-Jubail, where three Midrex modules already exists, using HYLIII technology and will be on stream in 1998.

6.3.1.5 Africa

Egypt

- Alexandria National Iron & Steel CO. (ANSDK) completed construction on a 0,8m tpy Midrex module at El Dikheila, Egypt, called ANSDK II, in 1997.

South Africa

- **Murray & Roberts** is planning to build a DRI-based integrated steelworks in Port Elizabeth. It has decided to build an HBI plant at Richards Bay, 900km to the north, rather than adjacent to the steelworks, thus being able to utilise the abundant gas supplies in the area, as well as having access to a deep water port being able to serve the 1,2m tpy export-orientated DRI plant.
- **Industrial Development Corp. (IDC)** and **Iscor** is constructing **a 0,8m tpy Midrex** shaft furnace which will use export gas generated by an adjacent COREX C-2000 module to feed their 1.25. tpy EAF-based flat products steelworks at Saldanha Bay.
- A new **0,15m tpy DRC kiln** was started up in 1997 at **Scaw Metals (AAC)** at Germiston, South Africa. Construction was engineered by Kvaerner Davy, the developers of the DRC technology.

Mozambique

- The **Industrial Development Corporation (IDC)** of South Africa is considering to build an iron reduction plant (Creamer[20]) in Maputo, Mozambique. The plant will be fed from a 270 million ton magnetite stockpile at Phalaborwa, South Africa, to which 7 million tons will be added annually from Foskor and Palabora Mining Company (PMC). Magnetite will be converted to iron, using natural gas from the Pande field, developed by US gas company, Enron.
- In another big venture using Mozambican gas, South African mining house **JCI** has proposed to build a 2,5m tpy DRI/HBI plant (Chatzistergou[18]) at Beira in Mozambique using the **Finmet process.**

6.3.1.6 Europe and CIS

In Europe, the Midrex technologies are already used in plants in Germany and Russia.

Germany

- Hamburger Stahlwerke GmbH is upgrading its **Midrex module by 0.1m tpy.**

Russia

- The **first HYL HBI plant** in the region is likely to be built in Russia where the iron ore producer, **Lebedinsky GOK,** is planing to build a **1m tpy HYL plant,** partly export-orientated, for probable start-up in 1998/99.

6.3.1.7 Oceania

Australia

Curiously, Australia, which is a major producer of iron ore and has both natural gas and coal reserves, has no DRI plants. This will be changing in the next few years as shown in the following projects:

- **United Steel Industry** is planning to build a **3,6m tpy** export-orientated **HYL-based** DRI plant in Western Australia.

- **Kingstream Resources** have plans for a **2,4m tpy DRI** based steelworks in Narngulu, Western Australia using a combination of **Midrex and HYLIII** technology and coming on-stream in the year 2000.

- **BHP** has ordered the first plant to use the **Finmet process**, utilising gas and low cost iron ore fines to produce HBI. The site at Port Hedland, Western Australia will host a **2,5m tpy plant** which is currently being built.

Table 6.8 shows that Australia, where no interest was shown in DRI capacity in the past, is the country set on contributing the highest capacity (7,3mt) of all the new projects constructed or under consideration, due to its proximity to both raw materials and the vast consumer market of EAF-steel producers in the pacific rim countries.

One of the key events that spurred this change of mind was the deregulation of gas supply by the West Australian Government. Len Dean [24], MD of BHP, said that in the relative short time that this step was taken, gas prices have fallen considerably.

More recently, however, since the financial unstability in many of the Asian countries, the markets for Australian dri appear less rosy. The sudden slump in the market is regarded as a short term mishap though, and most producers are convinced that in the long run, the Asian countries will remain regions of tremendous growth.

Even if some of the planned DRI projects are shelved, there threatens to be a massive supply of DRI and HBI available in the next few years. Considering only the most likely projects to go ahead, a total of nearly 30m tpy of DRI will be added to world supply (which totalled some 33,3 mt in 1996) by the year 2005 (table 6.9).

Table 6.9 - The Outlook for Global DRI/HBI Capacity

	mtpy
1996 Installed Nominal Capacity	37.5
+ Nominal Capacity under construction	19.6
+ Net Capacity Creep to 2005	11.4
Subtotal (sustainable output)	68.5 (65)
+ Projects under consideration	47.9
	116.4 (110)

Some of these are designed to supply specific steelmaking projects, but most will make at least some of their production available on the world market.

6.3.2 Additional capacity considerations

Many of the gas-based technologies used, especially Midrex and HYL III, regularly exceed the capacity at which they are designed to produce. This is due to increasing experience, and design improvements and leads to the phenomenon called **"capacity creep"**. Capacity creep, which has in the past been overseen as negligible, is currently contributing an increasing proportion to global actual capacity.

Most of the considered projects contributing to the additional capacity have very attractive rates of return which will probably continue for the next few years pushing the capacity up a further 30 mt after 2000. Consequently, **capacity utilisation**, which was 81 per cent in 1995, is expected to fall to 77 per cent in 2000 and 70 per cent up to 2005 (CRU [22]).

The logical question is: **Will there be enough market demand for all of this new supply ?**

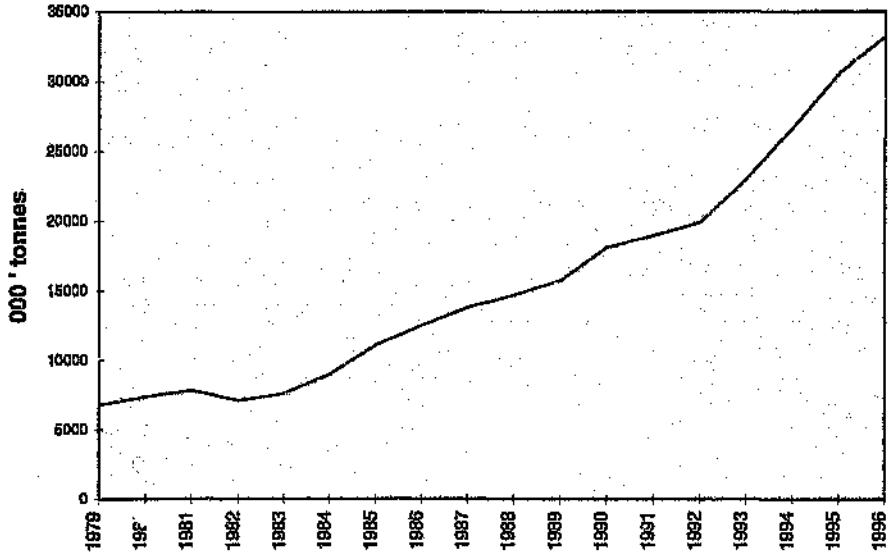
6.4 The Market for DRI

6.4.1 DRI Production and Trade

Trade in solid metallics during 1996 was at approximately 66mt, representing more than 25 per cent of the total purchased volume. This includes some 15mt of **molten pig iron**, close to 4mt of **DRI** and some 47mt of **scrap.**

Figure 6.4

World DRI production.



World DRI exports have been climbing steadily to some 4mt in 1996, representing 12 per cent of the 33,3mt of global DRI production for that year (figure 6.4).

6.4.2 DRI Demand vs. Capacity

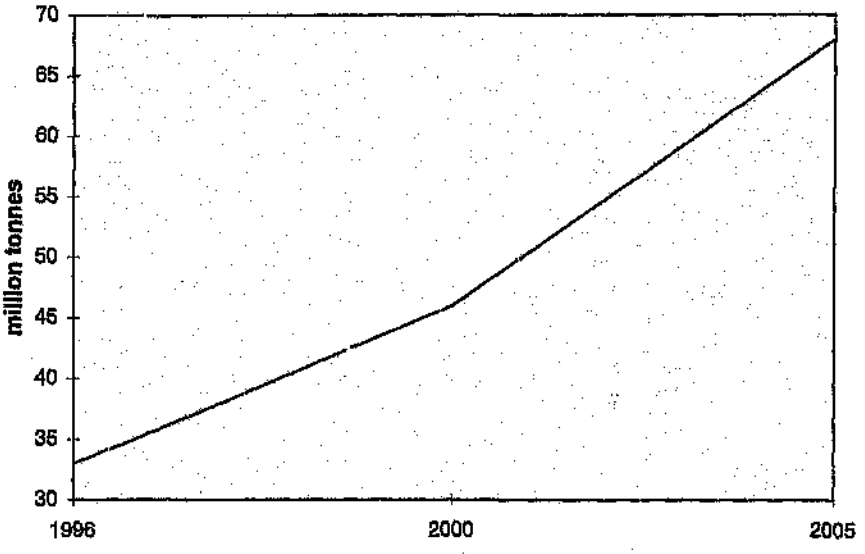
Capacity should increase at a quicker rate than demand nearer to the year 2000 and more so after 2000. Some 20 mt of capacity are being commissioned or under construction (see figure 6.4), and another 4 million tpy of additional capacity can be expected to materialise due to production efficiencies. About half of the capacity under construction and most of those considered for later, are not captive but aimed at a fast growing merchant market.

6.4.2.1 Increasing Demand for DRI

The CRU [22] is expecting global demand for DRI/HBI to rise to around 46mt by the turn of the century, and 68 million tons by 2005 (figure 6.5).

Figure 6.5

Global demand for DRI



Most of the increase in demand will occur in Asia and North America. In Asia, and other developing countries, this increase will develop mostly due to installation of new EAF facilities with insufficient local supplies of scrap. North American demand will be driven by the need for low residual iron units as quality requirement in mini-mills producing steel for flat products and special bar.

The CRU [22] sees the driving forces in the growth in demand to be:

- The expected **rise of 2 per cent per year in steel production** up to 2005, compared with no growth in the previous decade.
- **CIS steel production** should start picking up again after the previous collapse when output fell by more than 50 per cent.
- The demand for steel in **developing countries** will continue to grow rapidly.
- **EAF proportion** of global steel production will continue to increase up to some 42 per cent in 2005.

6.4.3 Steel Consumption

The International Iron & Steel Institute [48] estimates world steel consumption at the end of the century at around 714mt, 62mt more than in 1995. Considering continued rapid growth in the EAF industry it will absorb 39 per cent or 24mt of the additional demand.

6.4.3.1 New EAF capacity

Much of the **new EAF capacity** is appearing in **developing countries** without the pool of domestic scrap that steelmakers in most developed countries can rely on for their ferrous units. These countries have to import scrap at high cost. However, when scrap, which is traditionally low cost compared to other iron units, has to be imported over long distances it loses its competitive advantage over DRI.

The only developed country where a significant amount of **new EAF capacity** is coming on stream is the **USA**, which has historically been a net exporter of scrap, thus having an oversupply and seemingly in no need of alternative sources of iron units. The increase in flat-rolling mini-mill projects and increasing pressure on low residual scrap availability however are increasingly forcing these mills to look to DRI.

6.4.4 Life after the Southeast Asian Crisis

The IISI has revised its forecast for **steel demand** in 1998 downwards in the light of the financial difficulties afflicting Southeast Asia. The 1998-figure for world steel consumption proposed at their annual conference in October 1997 was a record 700.3m tonnes, 6 per cent higher than 1997. This figure has now been down-scaled by 1.6 per cent to 689,1 m tonnes. (MB [60]).

In terms of **DRI production**, CRU, at AIC's Third Asian Steel Summit in Hong Kong in June 1997, came to the conclusion that by including AUSI, An Feng Kingstream, but not including Mt Gibson or Minaralogy, the market needs no new capacity. That was before the Asian economic slump took effect. They argued that the DRI market is on the verge of becoming a buyer's market (Van Staten [97]).

Table 6.10 shows how events in Southeast Asia have curtailed projects planned in the ferrous industry of some of the major countries. Projects amounting to more than 20 mt of additional ironmaking capacity (which include DRI) will surely not see the light in the wake of the turmoil and uncertainty currently experienced in the market.

Table 6.10 - Existing and planned iron and steelmaking facilities ('000 tonnes)

Type	Thailand		Malaysia		Indonesia		Philippines	
	Present	Planned	Present	Planned	Present	Planned	Present	Planned
Iron making[1]	0	7000	0	1300	2300	9000	0	3700
Steelmaking	3160	4000	3750	2700	6370	9020	1220	1500
Plates	800	300	350	0	500	970	1700	720
Hot rolled	2400	4100	0	58000	2000	4900	-	-
Cold rolled	1000	2744	500	1000	1700	3970	850	1670
Galvanized	617	1130	450	1200	711	710	600	780
Colour sheet	137	30	130	140	172	160	80	260
Other [2]	540	250	240	0	130	670	240	0

(1) Including DRI
(2) Surface treated - Includes tinplate and stainless

Source: Japan Iron & Steel Exporters' Association

The following are some of the opinions held by major role-players and other specialists on the effect of the Southeast Asia crisis on the ferrous industry:

Mr Robert J Grow, president of US-based **Geneva Steel** remarked that the obvious effect on the US steel industry will be increased exports from Asian steel producers to the US. It is ironic, he says, that US policy-makers who urged Asian governments for decades to spur growth in personal domestic consumption and reduce the emphasis on export-led growth are now approving IMF packages that will do just the opposite: stifle domestic demand and cause export surges, particularly to the US (Grow [37]).

In South Africa, **Iscor's** export sales of steel dropped by 10 per cent in the first quarter of 1998 to 505 thousand tonnes, primarily as a result of the Asian financial crisis. This afflicted area traditionally represents 50 to 60 per cent of Iscor's export market (MB [61]).

According to Australian-based international ferrous and non-ferrous scrap trader and recycler, **Sims-metal**, the economic meltdown in some Southeast Asian countries has "without a doubt" changed the global metal market. Sims says that about 30 per cent of their exports are destined for the Asian market, and that the problem could be solved in the medium term.

Rio Tinto's Australian MD, Barry Cusack, admits that, although the economic meltdown in some Asian economies has not effected the company's operations to date, it has been foreshadowed that iron ore sales from wholly-owned **Hamersley** subsidiary will be less in 1998 than in 1997. Also, Hamersley iron has found that a conventional DRI plant would not be viable for several years based on inadequate demand in Southeast Asia (Van Staten [97]).

Rio Tinto is setting its sights on China, which it hopes will make up for any fall in Japanese iron ore demand. Company CEO, Chris Renwick, predicted that Chinese demand will double in the next 25 years and that China will take all Australia can offer.

BHP expects the downturn to continue for the next three to four years (Sproull [90]).

Paul Millbank of **Metal Bulletin** says that proposed joint venture iron ore and DRI projects in Australia and Oman, for which Southeast Asian partners were considered earlier, will be looking for other partners (Millbank [64]).

The opinion of European **plantmakers** is that long-term trends and investments in steelmaking in Asia will not be affected by the current economic situation in the area, and that, although they are currently suffering to some extent from the Asian slowdown, they talk of orders from the area as being frozen rather than cancelled. They are convinced that Asia, together with Europe and the USA, will continue to be one of the most important growth areas for them in the foreseeable future.

It seems thus as if, contrary to the bout of pessimism that occurred in the heat of the Asian crisis, the medium to long term view of the ferrous market still remains rosy, and although short term cutbacks in production has occurred, the long-term growth in production of DRI will not be adversely affected by it

6.4.5 Conclusion

Considering all the factors mentioned, is seems as if all the additional DRI capacity which is planned to come on stream until the end of the century, will indeed have a market. The market, however, is not insatiable and many factors such as energy costs, transport, and scrap prices and availability should be considered to determine the economic viability of a future DRI project.

CHAPTER 7: ECONOMICAL AND FINANCIAL CONSIDERATIONS

7.1 Location - A Strategic Consideration

Probably the most important strategic factor determining the feasibility of a DRI project is its location. Its should be kept in mind that any kind of transportation adds an additional cost to the final selling price of the DRI product, whether it be transporting of the raw materials to the DRI plant, or the DRI/HBI product to the consumer market.

7.1.1 Proximity to consumer market

As is clear from foregoing chapters, there exists in the world a vast and growing market for scrap substitutes, hungry and ready to buy DRI at reasonable prices.

For the producer of the DRI, however, it is essential to be situated as close as possible to this market. Due to the relatively low unit value of DRI, the cost of transportation plays an important role in the final cost structure, an thus the selling price of the DRI. If a DRI plant is situated too far from its market, the transportation cost factor becomes too big and the project loses its attractiveness. This is especially true in the case of producers of merchant DRI or HBI, who compete with other producers on prices.

As an example of this, Australia for instance, has a competitive advantage over other DRI producers in terms of its strategic location concerning far east countries. Producers in Venezuela or Trinidad will not be able to compete with the Australian prices due to the additional component of shipping costs. Similarly, however, the opposite situation exists regarding US markets, where the South American producer will have the advantage over his Australian competitor. An extra $10 add-on for transport can push up the selling price to a level too high to be competitive.

7.1.2 Proximity/ availability of iron ore

The price of iron ore is the most important contributing factor in the operating cost structure of a DRI project (50%). Depending on the type of technology to be used (based on lump, pellets, fines or a combination of these, and the degree of metallisation) the DRI producer should not be situated too far from the supplier. Due to the relatively low unit value of iron ore, the price increases dramatically with increase in transport cost due to distance. The ideal case would be if a DRI plant could be built adjacent to a iron ore mine that supplies its iron units.

7.1.3 Proximity/ availability of cheap and abundant natural gas or coal sources

After iron ore price, the next most important factor contributing largely to the operating cost is the price of the reductant.

7.1.3.1 Coal/ coke

Although gas-based technologies have proved to be more efficient, allowing larger production capacities and contributing to 90% of world DRI production, the use of

coal or coke is viable in some specific cases. For instance, in the case of **India**, where large reserves of both iron ore and ordinary coal occur, they form the basis of the coal-based DRI technologies.

DRI processes utilising coal have been a better solution for countries which possess high quality iron ore but little coking coal for conventional ironmaking or natural gas for the more established gas-based DRI technologies like Midrex or HYL.

The coal-based plants can accept lower grades of iron ore (medium grade 62-65% Fe) compared to more superior requirements (lumpy ore with more than 67% Fe) of gas-based plants. **South Africa** is another case where local iron ore and coal resources are used to produce coal-based DRI (Lobo [54]).

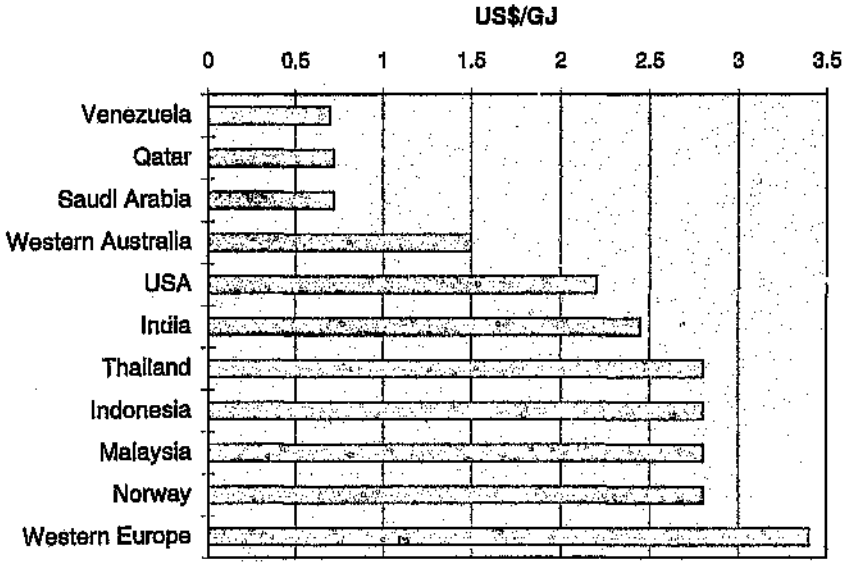
7.1.3.2 Natural gas

Kenneth Iverson [47] of Nucor Corp., the company that developed the Iron Carbide technology, remarked on the USA as a potential site for the development of a DRI plant, "... our investigations at the time discounted the United States because of the volatility of gas prices..".

Natural gas-based DR has not been able to succeed in the **USA** primarily because of the comparatively high cost of natural gas and labour, compared to such locations such as Trinidad or Venezuela. The only two North American plants are Midrex units at Georgetown Steel Corp. (Georgetown, SC.) and Sidbec-Dosco Inc. (Quebec). Most of the other gas-based direct reduction plants are in the oil-rich regions near the equator (FIOR[30]).

Figure 7.1

World Natural Gas Price - 1997



Mini-mills in the US have, generally, preferred offshore supplies of DRI and HBI, even when the added costs of briquetting and shipping are taken into account.

Scarnati [87] indicated that **Mexico** currently has gas prices comparable to, or higher than those in the US. The electricity and financing costs are also higher, yet the use of DRI is increasing in Mexico. This is based, in large part, on the price of scrap and the efficiency gained by many years of experience using DRI.

7.1.4 Favourable local socio-political situation

DRI projects are extremely costly, and are normally embarked on by a number of parties supplying the capital for the construction. Therefore shareholders normally attach a large significance to the social and political stability of the area and locations which are often favourable in terms of costs of inputs, could be rejected due to potentially large risk of an unstable socio-political environment.

7.2 Capital Costs

The capital cost involved in building a DRI plant is large; around US$200/t/y to US$300/t/y. If this is compared with a complete scrap-based mini-mill , it is in the same order of magnitude (Ullah and Yepez [96]). In addition to the DRI production units, in many cases a large part of the investment is made in the building of other infrastructure and transport facilities such as railroads, ports and harbours. In the consideration of an ideal location for a DRI plant, the existence of these facilities would contribute favourably to the viability of such a project.

The apparatus associated with the raw materials contribute the highest cost to the plant. With naturals gas, the cost of a reforming unit is an important part of total capital costs. In cases where coal-based technologies are used, costs increase due to handling and preparation, as well as cleaning of DRI to remove ash (Astier[2]).

7.2.1 Capacity creep - adding capacity at low cost

In general, most projects do not start at full capacity, but rather take some time to reach nameplate capacity. On the other hand it is often possible to produce more than the guaranteed nameplate capacity after some years of production efficiency, a phenomenon called "capacity creep". This refers to the difference between effective capacity (i.e. sustainable output) and nameplate capacity when effective capacity is higher. A profound financial incentive exists for DRI producers to exploit "capacity creep". It is a very cost effective way to add capacity.

Capital costs for enlarging an older plant (brownfield project) are minor relative to the cost of building a new plant (greenfield project). Capacity creep also helps to reduce the capital costs of a new plant. For example, assume your company has just invested $250m in a plant with rated capacity of 1mtpy. If the plant produces 1,5mt instead of 1mt, the investment per ton falls from $250 to $167 (Griscom [95]).

7.3 Commercial Strategies and Risk

The three basic commercial options for obtaining DRI are:

- **Own and Operate** - Build your own DRI facility, taking 100 per cent of the associated risk: capital, technical, operating, and off-take/consumption. The benefit of owning and operating a DRI plant is **secured supply** and the **ability to obtain it at cost**, rather than paying market prices. The operator is, however, dependent on the [illegible] facility for his supply and must pay all costs of the operation, including return on capital.
- **Off-take Agreement** - Through an independent owner/operator, enter into long term off-take agreements with a supplier, taking some risk, usually in the form of a take-or-pay commitment. Often, an equity investment by the off-taker is also required.

- **Spot Purchases** - Obtain DRI from independent merchant suppliers, taking on no plant risk. Buy only product that is available; negotiate competitive prices and quality. Here, the mini-mill risks are availability, quality and price of merchant DRI supplies.

7.3.1 Guarantees for bank loans

Through various sources it has been reported that banks are requiring that 60-80 per cent of the capacity of a new project be pre-sold to steel mills (CRU[22]). Financial institutions should also keep in mind that the investment criteria currently used are likely to lead to surplus of projects coming on stream , and should monitor the volume of projects committed, seeing that risks are higher than perceived at the moment.

The **main risks** that will appear with owning and operating your own facility are:

- **Process risks**, especially with new technologies,
- **Operating cost risks** (e.g. natural gas facilities in the US)

7.3.2 Economic Crisis

Another type of risk occurs in the case of an economic or financial crisis. A good point in case is the economic crisis that arose in Southeast Asia since mid-1997.

During the eighties, Singapore, Taiwan, Hong Kong and South Korea became known as the "Asian Tigers", a term coined to describe their aggressive, export-orientated economic performance at the time. Shortly after, in the mid-eighties, the "membership" was expanded to include Malaysia, Thailand and Indonesia.

Since mid-1997, however, when the collapse of the baht exposed Thailand's financial vulnerability, a domino effect started to spread through first Southeast, and then Northeast Asia, as currencies and share markets collapsed. This caused pandemonium in most of the main markets, and ambiguity still exists as to the future effects of the crash.

The ferrous markets were not excluded from the confusion, and currently, although everyone realise that markets have been influenced, participants do not always

agree about the level of severity, and how to adjust their production or market considerations.

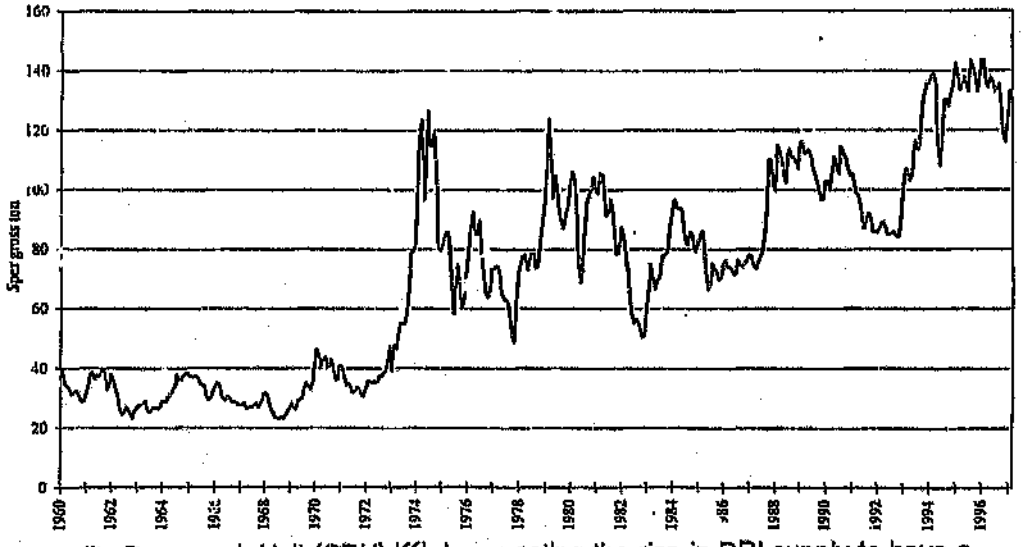
7.4 Selling price

The future for merchant DRI shipments depends largely on the ferrous scrap market situation, in terms of availability, price and quality. In the past, the ample supply and low price of scrap has been a dampening factor on the growth of merchant DRI shipments. Therefore, in the past, it was seldom economically viable to give preference to DRI.

The situation has, however, changed since the increasing scarcity of good quality scrap, which resulted in increasing scrap prices to levels between $120 and $140 after 1994. Figure 7.2 shows the volatile nature and increase in scrap prices over 36 years.

Nucor Corp.'s Kenneth Iverson [47] said in his address at the Gorham/Intertech Conference on Iron & Steel Scrap and Scrap Substitutes in March 1997 that he does not believe that scrap will sell at $200 per ton, nor at $110 per ton again. The logic behind his statement is that if scrap prices were to go up too high, such scrap charges will be replaced by less expensive DRI sources. The scrap market system will also not allow the price to go too low, as that will discourage scrap collectors to continue their operations.

Figure 7.2 - Average scrap price



Commodity Reasearch Unit (CRU) [44] is expecting the rise in DRI supply to have a **downward impact** on DRI prices due to mainly two reasons:

- most of the new capacity planned will be merchant product, not dedicated to any specific outlet.

- DRI/HBI will be used in the metallic charge in EAF's in increasing quantities, up to 20 per cent by the year 2000 compared to traditional levels of 10 per cent.

These factors could lead to the development of a genuine spot market for DRI/HBI. Prices in such an environment will settle at a floor set by production costs at marginal plants in times of excess supply. Most of the merchant DRI/HBI plants currently in operation and under construction incur net operating costs around $85 to $105/t. Due to the development of this spot market for merchant DRI/HBI, it is expected that the price will decline by around $5 to $10/t compared to scrap, mostly after 2000.

As the prophetic words of Iverson [47] indicated, even if scrap prices were to fall again, the historical levels around $100 will probably never be equalled again. Operating costs of scrap collectors and processors will just not be able to sustain such a low selling price.

7.5 Operating costs

- **Cost of iron ore** - in all cases it will be cheaper to produce metallics near the mine at FOB prices rather than in the importing countries at CIF prices; DR plants using fines-based technologies, have the added advantage of a lower cost input (natural fines or pellet feed) compared to the more expensive lump and pellets used by solid fuel-based processes (FIOR [80]).
- **Cost of coal**, - the price variations world-wide are usually not very large;
- **Cost of natural gas**, where variation from one place, where gas is abundant, to the usual conditions of industrialised areas, is very large

The following table shows the cost structure in a typical gas-based Midrex or HyL plant of capacity 1mt/y and capital cost of $200m.

Table 7.1 - Operating cost in producing 1 t DRI at 94% metallisation

	Quantity	Unit price	Cost ($)
Iron ore	0.94	50	47
Natural gas	10	2	20
Electricity	130	0.05	6.5
Manpower, royalties etc.			10
Briquetting			5
Total			88.5 $ per t HBI

- The highest cost contributor is that pertaining to iron ore. This can easily become uneconomically high if the ore has to be transported from far at a high cost.
- The cost for gas also imparts a large part to the final production cost.
- Briquetting adds an additional cost, but is essential in the passivation of the unstable DRI.

The following table shows the importance in deciding on the appropriate location for the DRI plant. It shows the large benefits in operating costs to producers who combine the inputs of natural gas and iron ore in favourable locations as well as the virtual impossibility to make a profit if all costs are high.

Table 7.2 Operating cost per ton DRI (gas-based Midrex or HYL) (capacity 1mt/y)

	Cheap natural gas (local)		Expensive natural gas (imported)	
Case	Local ore 1	Imported ore 2	Local ore 3	Imported ore 4
Raw materials				
Iron ore:				
unit cost ($/t Fe)	35	55	35	55
Natural gas:				
unit cost ($/GJ)	1	1	4	4
Operating costs				
Iron ore (0,95 t Fe/t)	33.25	52.25	33.25	52.25
Natural gas (10GJ/t)	10	10	40	40
Other operating costs	16,75	16,75	16,75	16,75
Subtotal	60	79	90	108
Depreciation (15% of US$200/t)	30	30	30	30
TOTAL *	90	109	120	138

Note: * US$/t of DRI/HBI at production site

- The first location is situated in a favourable position with regard to the availability of cheap gas and local ore.
- In comparison, in the last case where gas is acquired at high cost, and iron ore is imported at high cost, this creates nearly $50 per ton differential between producer 1 and producer 4.

In table 7.3 , Scarnati[67] compares, four gas-based HyL operations. The first three are located in the USA, while the fourth is located in Trinidad & Tobago.

Table 7.3 - DRI production costs through HYL technology

Product characteristics	DRI USA		High carbon DRI USA		High C Hytemp iron USA		HBI Trinidad & Tobago	
Metallisation, %	94		94		94		94	
Carbon, %	1.8		4.0		4.0		1.5	
Temperature, °C	<40		<40		600		<40	
Specific consumption	**unit/ton**	**Prod. Cost $/t**	**unit/ton**	**Prod. Cost $/t**	**unit/ton**	**Prod. Cost $/t**	**unit/ton**	**Prod. Cost $/t**
Iron ore pellets (70%)	1.02	49.06	1.02	49.06	1.02	49.06	1.02	41.81
Lump ore (30%)	0.43	13.59	0.43	13.59	0.43	13.59	0.43	10.53
Natural gas	2.48	17.29	2.61	18.2	2.67	18.62	2.57	7.4
Electric power	0	0	0	0	0	0	0	0
Water	1.6	0.03	1.6	0.03	1.8	0.04	1.8	0.02
Oxygen			10.92	0.36	10.92	0.36		
Labour								
-direct labour	0.3	5.1	0.3	5.1	0.3	5.1	0.3	2.4
-supervision	0.04	1.12	0.04	1.12	0.04	1.12	0.04	0.6
-indirect labour		2.04		2.04		2.04		0.96
General & Admin		1.65		1.65		1.65		0.79
Suppl. & Maint.		3.5		3.5		4		4
Briquetting								5
Direct Prod. Cost		93.38		94.65		95.58		68.51
Transport								14.61
Tot. Prod. Cost		93.38		94.65		95.58		83.12
Capital cost		16		16		16		19
Total		109.38		110.65		111.58		102.12

Scarnati [87] shows that operational cost advantages clearly exist, in the fourth case especially due to lower iron ore price, due to proximity to producers, low natural gas cost and labour (compare Direct Production Cost figures). Even after a large addition in transport and briquetting cost is included, it still shows a substantially lower production cost. The fourth case represents a 100% merchant HBI producer.

7.6 Low-cost options for the future

7.6.1 Location

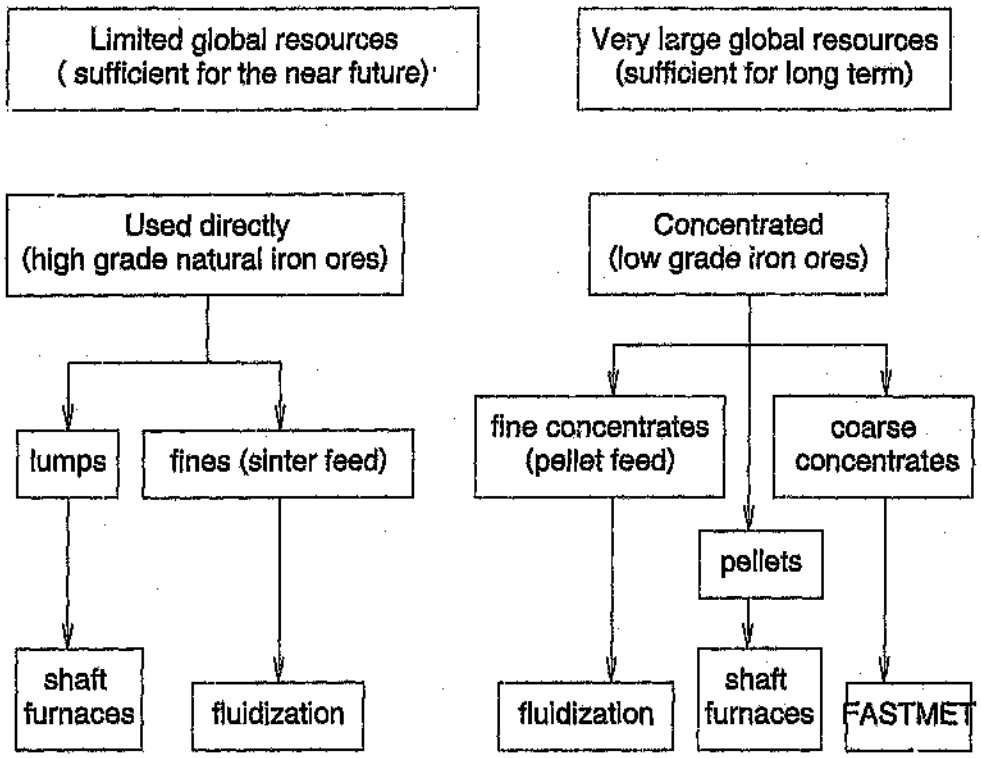
DRI/HBI producers planning to compete on the international merchant market would have to choose the location for their plants strategically. Proximity to cheap sources of gas or coal, as well as a ready supply of good quality iron units are prerequisites.

7.6.2 Fines-based feed

Technologies implementing low grade iron ore fines, rather that the traditionally used high grade lumpy and other higher grades, seem to be becoming increasingly popular. This is due to the cost-saving lower priced fines feedstock affords.

Compared to the unsure nature of future iron ore lump and pellet supplies, fines will be used predominantly in the long term (figure 7.3).

Figure 7.3 High-grade vs. low-grade iron ore feedstock



7.6.2.1 Fines vs. Pellets - Processes using iron ore fines rather than pellets or sized lump ore can save as much as $25 to 30/t of iron produced. High iron yield can be achieved by recycling fines and dust generated during the reduction process (Griscom and Lyles[38]).

7.6.2.2 Fines and low-cost gas - Hugh Brown, projects director of South Africa's JCI, says that the proposed Beira Iron project, to produce DRI/HBI via the Finmet process, could be the lowest-cost supplier to the Pacific Rim (Chatzistergou [18]). The key element in the cost structure will be the use of low-cost natural gas from Mozambique's vast unexploited gas reserves. This will counter-balance the cost of iron ore either from Iscor, or imported iron ore from CVRD.

The fines-based Finmet technology was decided on to produce HBI instead of iron carbide, due to the fact that the targeted customers in the Far East produce greater quantities of long and round product than flat product, which makes HBI the more competitive option. The reason for choosing a fines-based, rather than pellet-based process lies in the unsure nature of availability of pellets.

The following table shows comparative costs for a location in Mexico for the two fines based Lurgi technologies as given by Weber et al [99].

Table 7.4

			CIRCORED®		CIRCOFER®	
	Unit	US$/Unit	Unit/t HBI	Cost/t HBI	Unit/t HBI	Cost/t HBI
Fine ore	t	22,00	1,47	32,34	1,41	31,02
Natural gas	GJ	1,80	11,5	20,70	-	-
Coal	t	42,00	-	-	0,40	16,80
Oxygen	m^3	0,025	-	-	205	5,12
Electricity	kWh	0,02	05	2,10	90	1,80
Water	m^3	0,30	1,5	0,45	1,5	0,45
Manpower	man-h	6,00	0,25	1,50	0,25	1,50
Maint. & spares	$			9,50		8,50
Capacity	t/y			1 Million		1 Million
Debt service				31,20		26,40
Production cost				97,79		91,59

Both of these processes are fines-based and do not need an additional expensive beneficiation or agglomeration stage. This alone imparts a significant cost saving of $15 to $20 per ton of product. Coupled with additional advantages such as low energy consumption that results from closed energy circuits without the need for producing excess export gas can permit production of DRI/HBI at very attractive costs.

7.6.2.3 Fines and low-cost pulverised coal - According to Lepinski and Griscom [53], the Fastmet process, which utilises iron ore fines and pulverised coal in a rotary hearth furnace, could be developing into potentially the most economical method of producing DRI in North America. There seems to be an increasing interest in reserving natural gas for higher value-added products (i.e., petrochemicals) which makes the use of DRI processes using readily available non-coking coals even more attractive.

7.6.3 Direct hot charging

Griscom and Lyles[36] claim that the hot charging of Fastmet iron directly into the melting vessel can save the steelmaker $15 to $25/t of iron in energy, electrodes and refractory costs.

Capital costs for a Fastmet plant are minimised because all the high temperature processes are achieved in one single piece of equipment, the rotary hearth furnace, making the use of gas reformers, gas cleaning, and gas pumping unnecessary. Midrex estimates the capital cost of a 450 000t/y turnkey plant supplied to a US Gulf Coast location at around $65 to $75m (Griscom and Lyles [36]).

7.6.4 Top gas recycling

Although the original Hyl (batch) process did not recycle top gas, the newer HyL(continuous) process does so to reduce energy consumption. The other gas-based processes, Midrex and FIOR, also recycle all or part of their available top gas (Ullah and Yepez [98]).

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

This report has addressed the **fundamental changes** occurring in the steelmaking industry, but more specifically in electric arc furnace (EAF) steelmaking, in an attempt to show the **increasing role that direct reduced iron (DRI)** will be playing in the ferrous cycle of the future.

The whole chain of events that leads up to the production of DRI is initiated by an underlying demand for various grades of steel. This **demand** still seems to be **steadily increasing** as many countries in the world experience sustained economical growth, and consequently embark on steel-consuming construction projects and the production of steel consumer goods.

Steel production these days occur through two main avenues: the **blast furnace/ basic oxygen converter (BF/BOC), or the electric arc furnace (EAF).** Since the early 1900's, steel production via the blast furnace/ basic oxygen converter, or the so-called **"conventional steelmaking "** route has come under increasing pressure as the electric arc furnace (EAF) route and **"mini-mills"** started becoming more and more popular. The main reasons for the steady demise of the former route seems to be its detrimental effect on the **environment**, increasing pressure on reserves of **coking-coal**, as well as a **lack of flexibility** due to its size. In comparison, the electric arc furnace has a much **smaller economic size** requirement, which gives it the necessary **flexibility** to compete on a lesser scale. That, together with a **much lower capital cost** component, is making this route the favoured steelmaking r. ite of the future. It should however be noted that the blast furnace/ BOF route does still produce around 66 per cent of steel and that the conversion towards EAF steel will not happen over night.

The EAF steelmaking industry, however, also have their concerns and problems, especially with regard to **scrap.** The electric ..c furnace has traditionally been a **"100% scrap user",** and although DRI technologies had already been developed many years ago, it has traditionally been regarded as **"the more expensive alternative".** Also, scrap prices have **traditionally been low** enough to overshadow the viability of an alternative such as DRI.

More recently however, **high quality, low-residual scrap,** which had traditionally been used in EAF's to produce high quality steel has become **increasingly scarce** due to **production efficiencies** at the steel factories and manufacturing plants where it originated.

The subsequent **rise in price** of these higher quality scrap sources, has spurred the renewe i interest in using **DRI and other forms of "scrap substitutes".** The incentive is to blend DRI with lower quality, relatively more abundant, scrap sources, in an attempt to increase the iron units and decrease the residuals when producing higher quality steel. DRI has, apart from its **blending advantages**, also other benefits such as **uniform size, exact chemical composition and, in some cases, contained carbon,** which leaves it superior to scrap. DRI does have the detrimental tendency to **deo. ·ilise,** which can lead to **auto-ignition.** This can however be

passivated by briquetting, a very common practice especially in the production of the merchant product. Additionally, the utilising of DRI does produce a fair amount of **slag**, which introduce additional cost component.

The abundance **of new DRI projects** all over the world exemplifies the interest and the opportunity which have been shown by steel producers who, through integration with iron ore producers, or their own DRI plants, wants to **ensure availability of good quality iron units** for the future. Even from an investment point of view, the incentive exists to embark on projects for the production and sales of merchant DRI/HBI on the open market to steel producers who want to increase the quality of their steel and ensure the future supply of good iron units.

Care should be taken in the decision on DRI projects by steelmakers in their quest to ensure future low-residual iron units seeing that the economic viability of a DRI project depends, not just on the demand for good iron units, but on **strategic economic determinants**. The most important strategic factor is the **location** of DRI plants, as this translates into all the other important inputs. The positioning should be made in such a way that advantage can be taken of the **proximity of good quality, low cost iron ore**, as well as **natural gas (or coal)**. Additionally, the plant's positioning with regard to its expected **market** or set-off point, has to be strategically considered, seeing that the cost of transport can rapidly erase the potential competitive advantage or profit made by such a project. The concurrent **DRI technology** should also be chosen carefully, considering all contributing factors

Some of the **newer developing technologies** based on **low-cost fines** and/or cheaper **non-coking coal** (Circofer, Circored, Finmet) gives and additional cost saving which could make such technologies ideal for the future. Other cost-saving strategies such as **hot metal transfer** (Hytemp) **and top-gas recycling** (Midrex, HyL) also reduces costs significantly to give it a competitive edge. Making use of the off-gas from a smelter reduction unit such as **Corex**, and introducing it to an adjacent DRI unit seems to be a successful new combination.

The effect that the global "boom" of DRI projects will have on the ferrous industry can not be predicted with certainty. It will probably put some **surplus capacity** in place, and such a relative abundance of these metallics will definitely put **downward pressure on scrap prices**. With time, a **spot market for DRI** is likely to develop, which should **stabilise DRI prices** at a realistic level. This level will typically be close to the price level for high grade scrap. After the deficit in low-residual metallics is filled and demand and supply will be in equilibrium, the steelmaker's decision between scrap and DRI will be based less on emotion, and more on **economic and financial determinants.** DRI will, however, definitely **occupy a larger part of metallics used in EAF's in the future** than in the past.

Although the recent **collapse of the Southeast Asian markets** has taken away some of the enthusiasm of, especially Asian and Australian DRI producers, and their proposed projects, the need for low-residual iron units still exists. Those involved in decision making for DRI projects should make use of the **current opportunity** to benefit from **increasing scrap prices**, a well as the real **demand for low-residual iron units.** It should be kept in mind, however, that this unique scenario can not last

forever, and market forces will eventually cause scrap and DRI prices to find a new equilibrium once again.

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