PROPERTIES AND FEATURES OF DIRECT REDUCED IRON

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The blast furnace process is still the predominant method for primary iron production. However, the disadvantages inherent to the process led to the development of alternative processes such as the mini blast furnace process, smelting reduction process, and direct reduction process. Many of these alternative processes are still under development. However, direct reduction processes have reached some level of commercial applicability and are considered to be the most developed alternative ironmaking route. It is coke-less and environmentally friendlier when compared to the blast furnace process. In addition, direct reduced iron has a well-defined chemical composition when compared with steel scrap and has efficient melting properties in the electric arc furnace. Consequently, there is a great increase in the demand for direct reduced iron in electric arc steel making. These attractive features have led to an increase in worldwide production of direct reduced iron, which is currently approaching 50 million tons. Thus, direct reduced iron is gaining more importance. Hence, this article summarizes the basic properties and features of direct reduced iron.

Keywords: iron production, direct reduction, partial oxidation, catalytic, gas reforming, natural gas, coal, gasifiers
1. INTRODUCTION

Primary iron production is still predominantly made by the blast furnace process. However, there are disadvantages inherent to the blast furnace process such as: 1) dependence on high-quality metallurgical-grade coke and iron oxide feed stocks (pellets, sinters, briquettes); 2) economic viability only at large capacities; 3) environmental constraints on the coke ovens and sinter plants; 4) requirement of auxiliary plants (e.g., raw materials handling and preparation systems, sinter plants, coke ovens with strict environmental control systems, pellet hardening kilns); and 5) high capital and operational intensity, etc. (Chatterjee 1994). These disadvantages led to the development of alternative ironmaking processes such as the mini blast furnace process, smelting reduction processes, and direct reduction processes.

Mini blast furnace and smelting reduction processes include the reduction and smelting of iron oxide feed stocks utilizing charcoal (mini blast furnace process) or carbon-bearing materials (smelting reduction processes) producing slag-free pig iron.

On the other hand, direct reduction processes include reduction of iron oxides in the solid state, below the fusion temperature of pure iron (1535°C), utilizing hydrocarbon gases and/or carbon-bearing materials as reducing–carburizing agents. Direct reduced iron (DRI) is a highly metallized solid that still contains slag. Due to the fact that during direct reduction processes only oxygen inherent to the iron oxide feed stocks is removed from the system, the DRI produced has a similar but more porous physical form than the iron oxide feed materials utilized (Pietsch 1978 a,b). Thus, due to this porous structure, DRI is often called sponge iron.

It should be noted that although the current blast furnace processes is fully established, many of the alternative ironmaking processes are still under development. However, direct reduction processes have reached some level of commercial applicability and can be considered to be the most developed alternative ironmaking route when compared to others. In addition, due to increasing production and demand for DRI in electric arc steel making, DRI gained more importance over the past century. Hence, this article summarizes the basic properties and features of direct reduced iron.

2. PHYSICAL AND CHEMICAL PROPERTIES OF DRI

Some of the important physical and chemical properties of DRI are shown in Table 1 (Pietsch 1978 a,b). During direct reduction processes,
due to the lack of metal phase melting, slag is not separated from
the structure. This slag is formed by the fusing of the gangue minerals
inherent to the feed stocks with the aid of flux materials. Therefore, the
DRI chemical composition is dependent on the raw materials utilized.
The typical chemical composition of the DRI is shown in Table 2.

### 3. DIRECT REDUCTION PROCESSES

The pertinent chemical reactions for the reduction of iron oxides
are shown in Figure 1. These reactions have been introduced and dis-
cussed extensively in the literature by Zervas et al. (1996a, 1996b,

In Figure 1, the reduction reactions 5, 6, and 11, which utilize solid
carbon as a reducing agent, are called direct reduction reactions.
Reduction reactions 1, 2, 3, 4, 7, 8, 9, 10, 12, and 13, which utilize gas-
eous CO and H₂, are called indirect reduction reactions. And the carbur-
ization reactions 14, 15, 16, and 17 usually take place to cool and
stabilize the DRI produced.

The direct reduction processes are subdivided into three categories
according to their utilization of reducing agent source and/or generation
for the reactions shown in Figure 1. These categories are shown in Table 3
(Zervas et al. 1996a, 1996b, 1996c; True 1983; Steffen and Lungen 2004;
Lankford et al. 1993). Since utilization of the plasma technology has not
been successful at a commercial scale for DRI production and is still
under development to be made feasible on an economical scale, it is
not further discussed in this article. If hydrocarbon gases such as
hydrogen, carbon monoxide, or methane (natural gas) are utilized as
fuel and reducing-carburizing agent for DRI production, then the
process is called natural gas-based direct reduction. If carbon-bearing

---

**Table 1. Some important physical and chemical properties of DRI**

<table>
<thead>
<tr>
<th>Property</th>
<th>Direct reduced iron (DRI) values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.5–4.0 g/cm³</td>
</tr>
<tr>
<td>Bulk density</td>
<td>1.5–1.9 ton/m³</td>
</tr>
<tr>
<td>Specific surface area (Porosity)</td>
<td>0.5–4.0 m²/g</td>
</tr>
<tr>
<td>Crushing strength</td>
<td>50–110 kg/cm²</td>
</tr>
<tr>
<td>Degree of metallization</td>
<td>90–95% (average 91–93%)</td>
</tr>
<tr>
<td>% Metallic iron</td>
<td>~85%</td>
</tr>
</tbody>
</table>

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**PROPERTIES AND FEATURES OF DIRECT REDUCED IRON**

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<table>
<thead>
<tr>
<th>Plant</th>
<th>Metallization (%)</th>
<th>Total iron (%)</th>
<th>Carbon (%)</th>
<th>Gangue (%)</th>
<th>Sulfur (%)</th>
<th>Phosphorus (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QASCO DRI</td>
<td>95</td>
<td>92.50</td>
<td>1.54</td>
<td>4.70</td>
<td>0.015 (max)</td>
<td>0.035 (max)</td>
</tr>
<tr>
<td>Midrex natural gas-based DRI</td>
<td>92 or greater</td>
<td>92</td>
<td>0.8–1.7</td>
<td>3.15–6.5</td>
<td>0.002–0.01</td>
<td>0.007–0.04</td>
</tr>
<tr>
<td>HyL natural gas-based DRI</td>
<td>92–95</td>
<td>88.0–93.0</td>
<td>1.10–5.00</td>
<td>3.00–5.00</td>
<td>0.001–0.03</td>
<td>0.005–0.05</td>
</tr>
<tr>
<td>ISPAT-HSW</td>
<td>91–95</td>
<td>90–92</td>
<td>1.5–2.5</td>
<td>&lt;5.4</td>
<td>&lt;0.005</td>
<td>&lt;0.025</td>
</tr>
</tbody>
</table>
materials such as coal, gasified coal, or coke breeze are utilized as a fuel and reducing-carburizing agent for DRI production, then the process is called coal-based direct reduction (Mazurak 2003). Comparisons of some of the important properties natural gas-based and coal-based processes are shown in Table 4 (Chaterjee 1994).

4. REACTORS UTILIZED IN DIRECT REDUCTION PROCESSES

It can be seen from Table 4 that natural gas-based direct reduction processes utilize vertical shaft and retort (batch) furnaces and fluidized bed reactors. On the other hand, coal-based direct reduction processes utilize vertical shaft, multiple hearth and rotary hearth furnaces, rotary kiln, and fluidized bed reactors. Some of the important natural gas- and coal-based processes according to the type of direct reduction reactor they utilize are

Figure 1. Pertinent reduction and carburization reactions for DRI production.
shown in Figures 2 and 3, respectively (Panigrahi and Dasgupta 1999; Chatterjee 1994; Zervas et al. 1996a, 1996b, 1996c; Anonymous, 1983). These processes are described extensively by Anameric and Kawatra (2006a, 2006b). Most commonly utilized direct reduction reactors are briefly described below:

### 4.1. Vertical Shaft Furnaces


The vertical shaft furnace operates in a counter-current manner where the iron oxide feed stocks fall under gravity relative to the reducing carburizing gases. In this way, efficient heat transfer between the gas and solids is accomplished. Pellets, lump ore, or their mixture is utilized as iron oxide feeds.
Table 4. Comparison of some of the important properties of natural gas-based and coal-based direct reduction processes

<table>
<thead>
<tr>
<th></th>
<th>Natural gas-based direct reduction processes</th>
<th>Coal-based direct reduction processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactors utilized for reduction reactions</td>
<td>Vertical shaft furnace, retort (batch) furnace, fluidized bed reactor</td>
<td>Vertical shaft furnace, multiple heart furnace, rotary kiln, rotary hearth furnace, fluidized bed reactor</td>
</tr>
<tr>
<td>Reducing–carburizing agent</td>
<td>Reformed natural gas</td>
<td>Non-coking coals, charcoal, coke breeze</td>
</tr>
<tr>
<td>Iron oxide feed stocks</td>
<td>Pellets, lump, and fine ore</td>
<td>Pellets, lump, and fine ore, green balls, iron oxide waste materials</td>
</tr>
<tr>
<td>Reduction temperatures (°C)</td>
<td>850–950°C</td>
<td>950–1050°C</td>
</tr>
<tr>
<td>Operating pressures (atm)</td>
<td>1–16 atm</td>
<td>Slightly positive</td>
</tr>
<tr>
<td>Product % metallization</td>
<td>85–95%</td>
<td>88–92%</td>
</tr>
<tr>
<td>Ease of metallization control</td>
<td>Can be adjusted by reduction and cooling gas composition (Commercially practiced)</td>
<td>Hard to achieve</td>
</tr>
<tr>
<td>Product % carbon</td>
<td>1–2.5%</td>
<td>~0.2%</td>
</tr>
<tr>
<td>Ease of carburization control</td>
<td>Can be adjusted by reduction and cooling gas composition (Commercially practiced)</td>
<td>Hard to achieve</td>
</tr>
</tbody>
</table>
feed material. Chemical efficiency in the furnace can be accomplished by maintaining the proper bed permeability. Thus, fines generation and sticking of the materials that would disturb the gas flow should be minimized. The schematic diagram of a direct reduction vertical shaft furnace is shown in Figure 4 (Zervas et al. 1996a, 1996b, 1996c; Chatterjee 1994).

Figure 2. The natural gas based processes according to the reduction reactor type being utilized.

Coal Based Direct Reduction Processes (According to the Reduction Reactor Type)

- Rotary Kiln Furnace
  - SL/RN
  - Krupp-CODIR
  - DRC
  - ACCAR/OSIL
  - TISCO (TDR)
  - Krupp-Renn
  - LS-RIOR

- Fluidized Bed Furnace
  - Cirofer

- Vertical Shaft Furnace (Retort Process)
  - Kinglor-Metor
  - Hoganas

- Multiple Hearth Furnace
  - Pirunus

- Rotary Hearth Furnace
  - Inmetco
  - Fastmet
  - Sidcomet
  - Comet
  - IDI
  - ITMk3
  - DRyIron

Figure 3. Coal-based processes according to the reduction reactor type that is being utilized.
4.2. Retort (Batch) Furnaces

The retort (batch) reduction reactors are utilized in natural gas-based direct reduction processes: Hyl I & II. The HyL I natural gas-based process was the first commercialized direct reduction process (Zervas et al. 1996b; Chatterjee 1994).

The retort (batch) furnaces operate in a fashion similar to vertical shaft furnaces. However, for these furnaces, iron oxides are charged in fixed beds in series and the reducing gas is transported from one bed to another. Prior to their injection in each retort (batch), furnaces reducing gas is reheated and conditioned with steam. Fresh reducing gas

Figure 4. Schematic diagram of a direct reduction vertical shaft furnace. In this figure, the dotted lines indicate the flow of solid materials in the system and the solid lines indicate the flow of the gas in the system.
mixture is injected to the last retort furnace, which is the cooling furnace. In the cooling furnace, final reduction and carburization of the DRI takes place. The reducing gas mixture can be injected to the retort furnaces either from the top or from the bottom. When these gases first come in contact with the iron oxides, reduction reactions take place very rapidly. By the time the gases reach the bottom or top of the furnace, the reaction speed slows down with reduced reduction potential of the reducing gases. Thus, reduction in each reactor does not take place in a uniform fashion. The schematic diagram of a direct reduction retort (batch) furnace series is shown in Figure 5 (Zervas et al. 1996b; Chatterjee 1994).

4.3. Fluidized Bed Reactor

The fluidized bed reduction reactors are utilized in natural gas-based direct reduction processes: Fior, Finmet, Circored, H-Iron, HIB, Iron...
Carbide, and coal-based direct reduction processes: Cirocfer (Zervas et al. 1996c; Chatterjee 1994).

Unlike the other reactors utilized in the direct reduction processes, fluidized bed reactors can be utilized in beneficiation of fine ore without prior agglomeration. Since the surface area of the fine ore is higher than the pellets or lump ore, reduction reactions take place more quickly. The thermal and chemical efficiency in the reactor is usually attained by good mixing of the feed, which is achieved by a counter-current flow of the charge materials and the reducing gases. The reducing gas velocity in the reactor should be adjusted in such a way that optimum fluidization can be achieved and carryovers to the waste gas stream should be eliminated. To satisfy these requirements, most of the reactors operate at elevated pressures (Zervas et al. 1996b). Operational problems are faced with this reactor when operating at high degrees of metallization. This is due to the increased sticking tendency of the materials with the

Figure 6. Schematic diagram of a direct reduction fluidized bed reactor. In this figure, the dotted lines indicate the flow of solid materials in the system and the solid lines indicate the flow of the gas in the system.
increased metallization, as sticking of the materials would interfere with fluidization. The schematic diagram of a direct reduction fluidized bed reactor is shown in Figure 6 (Zervas et al. 1996b; Chatterjee 1994).

4.4. Rotary Kiln Furnace


The rotary kiln furnace is composed of a slightly inclined cylinder containing a shell with internal refractory lining (Zervas et al. 1996c). Thus, inclination of the furnace, i.e., the gravitational forces, is utilized for the movement of the charge in the furnace. The reducing-carburizing agents and iron oxide feed stocks in the form of pellets, lump ore, and self-reducing green balls (iron oxide, flux, reductant, and binder agglomerates) are charged together to the furnace. The reducing and carburizing gas generation and the reduction of iron oxides take place simultaneously in the furnace. The controlled combustion of the reducing agent, coal in the furnace is achieved by the controlled injection of air both at the discharge end of the kiln and through the blowers mounted along the kiln length (Chatterjee 1994). This combustion reaction generates the carbon monoxide required for the reduction reactions. In addition, combustion of the coal, along with the burner located at the discharge end of the kiln, provides the energy required for the reduction reactions. The reducing atmosphere in the kiln is maintained by running the burner with a deficiency of air. Air flow in the kiln is controlled to minimize temperature fluctuations, since localized temperature increases can result in the formation of accretions on the kiln lining and ball-shaped clusters within the bed. The kiln discharge is cooled in a rotary cooler. The schematic diagram of the direct reduction rotary kiln furnace is shown in Figure 7 (Zervas et al. 1996c; Chatterjee 1994).

4.5. Rotary Hearth Furnace

The rotary hearth reduction reactors are utilized in coal-based direct reduction processes: Inmetco, Fastmet, Sidcomet, DRYIron, Comet, IDI, and ITmK3 (Zervas et al. 1996c; Chatterjee 1994).

The rotary hearth furnace can be operated in a multiple reaction zone manner, such as the preheating zone, initial reduction zone, final
reduction zone, and cooling zone. Temperature, gas flow, and gas composition are controlled to provide the required conditions in each zone (Lehtinen and Rohop 1999). Pellets, lump ore, coal, and self-reducing green balls can be utilized as iron oxide feed stocks in this furnace. The reducing gas generation and the reduction of iron oxides take place simultaneously. The opposite rotation of the furnace hearth and the gases enables the counter-current interaction of the solids and gases. The layering thickness of the solids on the hearth dictates the reduction efficiency in the furnace. At low thicknesses, higher reduction efficiencies can be attained and the product usually has more uniform properties. Thus, the capacity of the process is directly proportional to the furnace hearth area available. The energy required for the reactions are supplied by the combustion of the coal and the burners located at the furnace walls. These burners are fired with pulverized coal, natural gas, or fuel oil with the deficiency of air to maintain the reducing atmosphere in the furnace. The schematic diagram of the direct reduction rotary hearth furnace is shown in Figure 8 (Panigrahi and Dasgupta 1999; Lehtinen and Rohop 1999).

5. IRON OXIDE FEED STOCKS UTILIZED IN DIRECT REDUCED IRON PRODUCTION

The final chemical composition and physical form of the DRI is dependent on the raw materials used. High-quality direct reduced iron can be
produced by the utilization of high-quality iron oxide feed stocks. Thus, the levels of gangue minerals and the percentage of oxide minerals present in the direct reduced iron can be adjusted with the quality of the iron oxide feed stocks materials utilized.

The direct reduced iron-producing reactions are solid state reactions (see Figure 1); the physical size distribution of the iron oxide feed stocks used as raw materials does not change (unless there are sticking and degradation problems) throughout the process (since only oxygen is removed from the structure). Accordingly, the physical size distribution of the iron oxide feed stocks utilized (pellets, lumps, sinters, green balls, briquettes, and fine ore) dictate the size distribution of the DRI produced. This determines whether there is a need for the briquetting of DRI produced, in order to reduce the surface area, to ease handling, shipping, transportation, and loading to the consequent operational reactor (electric arc furnace, blast furnace, foundry cupola, basic oxygen furnace).

Additionally, reducibility characteristics of the iron oxide feed stocks can be used to promote the efficiency and yield of the direct reduction processes. Iron oxide feed stocks with good reducibility, low sticking, degradation, and swelling properties are preferred. For example, if highly reducible iron oxide feed stocks are utilized, it is more likely to produce highly metallized DRI.
The reduction efficiency and economics are highly dependent on the reducing agent source and production. The natural gas-based direct reduction processes utilize reformed natural gas as the reducing agent. The coal-based direct reduction processes utilize coal bearing materials and/or gasified coal-bearing materials as a reducing agent. The availability and price of the reducing agent source dictate the economics of the process. The CO, CO₂, H₂O, H₂, and C composition of the reducing agent dictates the efficiency of the reduction (see Figure 1).

The reduction efficiency and economics can also be improved by maintaining the coupled reducing agent—solid reaction sites. The coupled reducing agent—solid reaction sites stability can be achieved by maintaining good permeability of the bed in the reduction reactor. As the permeability of the bed decreases, the usage of reducing gas increases, increasing the reducing agent source consumption. Consequently, the physical strength of the iron oxide feed stocks utilized influence the permeability of the bed and the reducing agent consumption.

The iron oxide feed stock requirements can be characterized in three categories, as shown in Table 5 (Pietsch 1978b; Zervas et al. 1996c; Poveromo and Swanson 1999).

### 5.1. Chemical Requirements

The chemical requirements for the iron oxide feed materials to be used in direct reduction processes are shown in Table 5. The composition and concentration of the gangue minerals trapped in the direct reduced iron produced (originally present in the iron oxide feed) effect the efficiency, energy consumption, performance, and economics of the consequent steel making (electric arc furnace) process (Poveromo and Swanson 1999).

The better the chemical quality of the iron oxide raw materials utilized, the better the chemical quality of the direct reduced iron will be. The high chemical quality iron oxide feed stocks can also be blended with cheaper lower chemical quality iron oxide feed stocks at optimum ratios to improve the economics of the operation (Pietsch 1978b).

### 5.2. Physical Requirements

The physical requirements for the iron oxide feed materials to be used in direct reduction processes are shown in Table 5. These requirements
### Table 5. Suitability of iron oxide feed stocks for direct reduction processes

<table>
<thead>
<tr>
<th>Chemical considerations</th>
<th>Suitability of iron oxide feed stocks for direct reduction processes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total iron</strong></td>
<td>&gt; 64%</td>
</tr>
<tr>
<td><strong>Total amount of gangue</strong></td>
<td>Acidic gangue: SiO₂ + Al₂O₃ + TiO₂ &lt; 2–3%</td>
</tr>
<tr>
<td></td>
<td>Basic gangue: CaO + MgO + other basic oxides &lt; 3%</td>
</tr>
<tr>
<td><strong>Total amount of alkalis</strong></td>
<td>P &lt; 0.03, S &lt; 0.008, Na and K alkalis low as possible</td>
</tr>
<tr>
<td><strong>Total amount of residual elements</strong></td>
<td>Cr + Pb + Cu + Sn + Ni + Mo + As + Sb + V + Li + Mn + other minor elements &lt; 0.16%</td>
</tr>
</tbody>
</table>

| Physical considerations          | | |
|----------------------------------|---------------------------------------------------------------------|
| **Size distribution**            | Fine ore: Utilized in fluidized bed reactors and rotary reactors    |
|                                  | Pellets, lumps, briquettes: Utilized in shaft, retort, and rotary reactors |
| **Mechanical strength, degradation** | Characterized by the tumble index and/or compression strength, important for achieving good bed permeability. |
| **Particle and bulk density**    | Important for determining and adjusting the bed characteristics      |

<table>
<thead>
<tr>
<th>Reduction considerations</th>
<th>Suitability of iron oxide feed stocks for direct reduction processes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reducibility</strong></td>
<td>The feed stocks with the high reducibility tendencies produce highly metalized DRI</td>
</tr>
<tr>
<td><strong>Sticking tendency</strong></td>
<td>Low temperature sticking results in a less efficient operation, reduced productivity, and increased fuel requirements</td>
</tr>
<tr>
<td><strong>Fragmentation</strong></td>
<td>Excessive fragmentation impedes proper reducing gas flow and distribution</td>
</tr>
<tr>
<td><strong>Product and reduction strength</strong></td>
<td>Product should not loose its strength during solid state reduction</td>
</tr>
</tbody>
</table>
differ based on the direct reduction reactors utilized. The iron oxide feed stocks that can be beneficiated by different direct reduction reactors are shown in Table 6 (Poveromo and Swanson 1999).

Shaft furnaces utilize iron ore pellets, lumps, briquettes, and sinters as iron oxide feed material for direct reduced iron production. The efficiency and yield of the shaft furnace operation is highly affected by the following properties of the feed materials:

1) Size distribution.
   The feed should have narrow size distribution for the formation of a permeable furnace bed to allow maximum reducing gas flow. This increases productivity and decreases the reducing agent consumption.
   Oversized feed material should not be introduced to the furnace, since due to the heat transfer properties, it would adversely affect the operation. Fine feed material also should not be introduced to the furnace, since it would decrease the furnace bed permeability, cause sticking problems, and reduce the furnace efficiency and yield.

2) Mechanical strength.
   The feed should have enough strength to support the weight of the furnace bed. This provides consistency on the permeability of the furnace bed and reduces cave-ins.

3) Physical degradation properties.
   Fragmentation of the feed should be decreased for promotion of the shaft furnace performance. The fine material formation during handling, shipping, and transportation; dropping to the furnace; and heating (thermal shock) should be minimized. The fines generated would either end up in the furnace gas system or would be converted to DRI fines, which might re-oxidize or get lost during transportation to the electric arc furnace (Poveromo and Swanson 1999). Additionally, the fines in the shaft furnace might cause sticking and buildup problems and reduce performance.

4) Particle and bulk densities.
   The weight of the furnace bed to be supported is directly proportional to the particle and bulk densities of the feed materials.

Cylindrical rotary kilns utilize iron ore pellets, lumps, briquettes, and sinters as iron oxide feed material for DRI production. Unlike the shaft furnace, operation efficiency (heat and the mass transfer)
Table 6. The iron oxide feed stock utilization based on the direct reduction reactor and important operational parameters, which can be adjusted with the physical characteristics of the iron oxide feed stocks

<table>
<thead>
<tr>
<th>Direct reduction reactor type</th>
<th>Iron oxide feed stocks used</th>
<th>Operational parameters which can be adjusted with the physical characteristics of the iron oxide feed stocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft furnaces</td>
<td>Pellets, lumps, briquettes, sinters</td>
<td>(1) Adequate bed permeability for reduction gases. (2) Adequate mechanical strength to support the weight of the bed. (3) Feed should not disintegrate when being fed to the reactor or when subjected to the thermal shock to reduce the amount of fines produced.</td>
</tr>
<tr>
<td>Rotary kilns</td>
<td>Pellets, lumps, briquettes, sinters</td>
<td>(1) Adequate bed permeability for reduction gases. (2) Adequate mechanical strength to support the weight of the bed. (3) Feed should not disintegrate when being fed to the reactor or when subjected to the thermal shock to reduce the amount of fines produced.</td>
</tr>
<tr>
<td>Rotary hearth furnaces</td>
<td>Green balls (iron oxide, reductant, binder, and flux agglomerates)</td>
<td>(1) The reducibility depends on the particle size of the ingredients. (2) Adequate green ball mechanical strength to withstand handling, shipping, and transportation. (3) Feed should not disintegrate when being fed to the reactor or when subjected to the thermal shock to reduce the amount of fines produced.</td>
</tr>
<tr>
<td>Fluidized bed reactors</td>
<td>Fine ore</td>
<td>(1) Narrow feed size distribution to prevent carryover of undersized particles to the bag house and to obtain good fluidization. (2) Prevention of sticking at reduction temperatures.</td>
</tr>
</tbody>
</table>
is not greatly influenced by the furnace bed permeability. However, fragmentation and clustering is of a greater influence for efficiency and yield of the cylindrical rotary kiln operations. The fines generated usually leave the kiln as unreduced dust, and cluster formations cause buildups and interrupt the uniformity of the product quality.

Rotary health furnaces utilize green balls as iron oxide feed material for DRI production. The feed materials to be used should have enough mechanical strength to withstand shipping, handling, and transportation. Additionally, they should not disintegrate when they are being fed to the furnace or when they are subjected to thermal shock. The ingredients used for green ball preparation should have a fine size distribution to improve the reducibility and, consequently, to reduce the furnace residence time.

Fluidized bed reactors utilize fine ore as iron oxide feed material for DRI production. The feed material to be used should have a narrow size distribution to eliminate the following problems (Poveromo and Swanson 1999):

1. The carryover losses of the very fine materials to bag houses.
2. The sticking problems of the very fine particles to the reactor walls.
3. The accumulation of the coarse materials in the bottom of the bed disturbing the fluidization.

Conversely, the fluidized bed reactors that operate at high gas velocities (circulating fluidized beds, the Circored process) are less sensitive to the feed size distribution, since the fluidization is promoted by the gas flow (Poveromo and Swanson 1999).

5.3. Reduction Characteristic Requirements

The reduction characteristic requirements for the iron oxide feed materials to be used in direct reduction processes are shown in Table 5. The significance of these properties according to the feed stock type utilized is shown in Table 7 (Poveromo and Swanson 1999). These requirements have a high influence on the reducing agent consumption, operational temperatures, residence times, and maximum attainable metallization. For instance, highly metallized DRI can only be produced by the utilization of highly reducible iron oxide feed stocks.
Table 7. The significance of the reduction characteristics on the direct reduction process according to the feed stocks utilized. (The swelling characteristics for all iron oxide feed stocks higher than 25–30% is undesirable.)

<table>
<thead>
<tr>
<th>Iron oxide feed stocks</th>
<th>Reducibility</th>
<th>Sticking</th>
<th>Degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellets</td>
<td>Dependent on the porosity, firing characteristics, and origin of the iron oxide.</td>
<td>Can be minimized by limestone or dolomite additions or the application of oxide coatings after pelletization</td>
<td>Somewhat significant</td>
</tr>
<tr>
<td>Lumps</td>
<td>Dependent on the porosity, density, and origin of the iron oxide.</td>
<td>Insignificant</td>
<td>Very significant; thermal fragmentation problems</td>
</tr>
<tr>
<td>Sinters</td>
<td>Dependent on the porosity, firing characteristics, and origin of the iron oxide.</td>
<td>Can be minimized by limestone or dolomite additions or the application of oxide coatings after pelletization</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Briquettes</td>
<td>Dependent on the porosity, density, and origin of the iron oxide.</td>
<td>Can be minimized by limestone or dolomite additions or the application of oxide coatings after briquetting</td>
<td>Somewhat significant</td>
</tr>
<tr>
<td>Green balls</td>
<td>Dependent on the porosity and origin of the iron oxide.</td>
<td>Can be minimized by limestone or dolomite additions or the application of oxide coatings after drying</td>
<td>Significant</td>
</tr>
<tr>
<td>Fine ore</td>
<td>Dependent on the origin of the iron oxide.</td>
<td>Very significant; can be minimized by limestone or dolomite additions</td>
<td>Insignificant</td>
</tr>
</tbody>
</table>
Some important influences of the reducibility properties of the iron oxide feed stocks on the direct reduction process efficiency can be summarized as follows (Poveromo and Swanson 1999):

1. The utilization of dense lump ores or over-fired pellets and sinters increases the residence time requirement in the furnace. This is due to low porosity and slower diffusion of the reducing agents and products.

2. During the reduction of hematite or magnetite to iron (see Figure 1), swelling is observed due to the rearrangement of the crystal structure and dimensional expansion (Poveromo and Swanson 1999; Nascimento et al. 1998; Sharma et al. 1992). The swelling of the lump ores cause thermal fragmentation, and chipping. These chipped particles reduce the bed permeability and reduction efficiency, especially in shaft furnace operations, as described above. However, when operating with pellets, briquettes and green balls chipping due to the swelling phenomenon is not observed as frequently. This is due to the presence of a binder keeping the structure together (Hayashi and Iguchi 2003; Singh and Bjorkman 2004).

3. The iron oxide feed stocks containing high amounts of alkali oxides (Na₂O or K₂O) can promote excessive swelling (a volume increase higher than 25–30%) in the furnace. This can adversely affect the shaft furnace operations, since the volumetric weight ratios change due to inefficient reactor surface area utilization. However, it does not affect the rotary kiln and rotary hearth furnace operations as much, due to the presence of excess freeboard space.

4. The sticking and clustering of the feed materials might form buildups in the reactor, reducing the yield. This might also reduce the uniformity of the product quality.

5. The sticking problems increase with increasing iron content. Some furnace operators decrease the sticking problems by flux additions; by mixing lump ores (15–30%) to the feed; or by applying finely ground limestone, dolomite, bauxite, and cement coatings.

6. REDUCING AND CARBURIZING AGENT FEED STOCKS UTILIZED IN DRI PRODUCTION

6.1. Natural Gas-Based Direct Reduction Processes

The natural gas-based direct reduction processes utilize natural gas reformers for the production of the reducing gases CO and H₂. According
to the nature of the gas reforming, these processes are subdivided into two categories: Partial oxidation gas reforming and catalytic gas reforming, as shown in Table 3 and Figure 9.

6.1.1. Catalytic Natural Gas Reforming. The catalytic steam gas reforming takes place according to the following endothermic reactions (Panigrahi and Dasgupta 1999; Zervas et al. 1996a):

\[
CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \quad \text{(Reaction 18)}
\]

\[
CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \text{(Reaction 19)}
\]

Catalytic gas reforming can be done in three different ways as shown in Figure 9 and Table 3.

6.1.1.1. Catalytic Steam Gas Reforming—Reforming of the gas and steam on a bed of nickel catalyst supported on a refractory base such as alumina: The basic schematic flowsheet of the natural gas-based direct reduction processes, which utilize catalytic gas reforming for the production of a reducing gas mixture, is shown in Figure 10.
Fresh natural gas feed and steam is fed to the gas reformer where the primary reforming Reaction 19 takes place, producing a H₂- and CO-rich reducing gas mixture. A commercial and conventional nickel-based catalyst supported on a refractory base, such as alumina, is utilized for the gas reforming Reaction 19 in these processes (Rodriguez and Scarnati 2004). The reducing gas mixture produced by the gas reformer is heated in a heat exchanger further before being fed to the reduction reactor. The cleaned reduction furnaces off gases are burned along with the fuel in the heat exchanger to provide the energy required.

Oxygen is typically added to the reducing gas mixture at the inlet of the reduction reactor to promote the partial (oxidation) combustion Reactions 20 and 21. This increases the temperature of the reducing gas mixture and promotes additional gas reforming with the utilization of Reactions 19 and 22. Consequently, this increases the reduction efficiency of the process and decreases the reducing gas consumption.

\[
\text{CH}_4 + \frac{1}{2}\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2 \quad \text{(Reaction 20)}
\]
An important advantage of the catalytic gas reforming is the flexible independent operation of the gas reforming and reduction reactors. Therefore, in the gas reforming reactor, reforming of the fresh gas and steam mixture according to Reaction 19 takes place, and a H₂- and CO-rich reducing gas mixture is produced. On the other hand, reduction and carburization of the iron oxide feed stocks utilizing the reducing gas mixture according to Reactions 1–17 takes place and DRI and reduction reactor off gases are produced. The reduction reactors off gases are only utilized in the heat exchanger reactor to supply the energy required; they are not recycled back to the gas reformer reactor. This flexible operational scheme results with the following operational advantages (Quintero and Scarnati 1998; Rodriguez and Scarnati 2004):

1) Ability to utilize a wide variety of reducing gas feed stocks while keeping the same basic reduction process scheme: Reformed gas, gases from coal gasification, hydrogen, coke oven gas, gases from the hydrocarbon gasification, gases from smelter–gasifiers, partially spent gases from other direct reduction plants
2) Ability to utilize high sulfur iron oxide feed stocks without prior treatment, since reduction reactor off gases are not recycled to the gas reformer, there is no danger of catalyst poisoning
3) Longer catalyst life, since the impurities and dust from the reduction reactor are not recycled to the gas reforming reactor
4) Smaller gas reformer reactor size.

An additional advantage of the catalytic gas reformers is their ability to generate the electricity needed for the direct reduction plant. The steam needed for the gas reforming reactions is sent to a turbo generator prior to its utilization for gas reforming. This enables the direct reduction plant to be completely independent from the outside supply of electricity (Rodriguez and Scarnati 2004). For example, the Vikram Ispat–Grasim plant (HyL III natural gas-based direct reduction plant) produces all of the electric energy required for the plant to run and even exports energy (see www.hylsamex.com, accessed 2004).
An important disadvantage of catalytic gas reforming is that care must be taken to enhance the catalyst life by adjusting the steam-to-carbon ratios and sulfur content of the natural gas feed to the reformer. For example, the sulfur content of the natural gas fed to the reformer has to be lower than 1 ppm to inhibit the catalyst poisoning (Zervas et al. 1996b). When operating at low steam-to-carbon ratios, carbon deposition on the catalyst should be avoided by operating at high temperatures. The carbon deposition on the catalyst takes place according to the following reactions (Zervas et al. 1996b):

\[
\begin{align*}
\text{CH}_4 & \rightarrow C + 2\text{H}_2 \\
\text{CO}_2 + C & \rightarrow 2\text{CO}
\end{align*}
\]

(Reaction 23)

(Reaction 24)

The removal of the carbon deposited on the catalyst takes places according to the following reaction (Zervas et al. 1996b):

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

(Reaction 25)

6.1.1.2. In situ gas reforming—reforming of the gas in the reduction reactor with the utilization of partial combustion and hot direct reduced iron as a catalyst: The basic schematic flowsheet of the natural gas-based direct reduction processes that utilize in situ gas reforming for a production reducing gas mixture is shown in Figure 11. The iron oxide feed stocks are reduced in these process with the utilization of reducing gas mixture produced by the aid of the partial (oxidation) combustion reactions (Reactions 20, 21, and 22) and the in situ natural gas reforming reaction (Reaction 19). The partial (oxidation) combustion at the inlet of the reduction reactor provides the energy required for the in situ gas reforming reactions. These reactions utilize hot direct reduced iron produced in the reduction reactor as a catalyst and take place in the cooling zone of the reduction reactor.

The main advantages of the in situ gas reforming systems can be summarized as follows (Duarte et al. 2002):

1) The endothermic character of the gas reforming reactions provides the environment required for cooling of the hot DRI produced with no extra effort

2) No need for external gas reforming units

3) Lower capital and operational costs due to the elimination of external reformer facilities and a DRI cooling system
4) Since there is no danger of catalyst poisoning, high sulfur natural gas and iron oxide feed stocks can be utilized.

5) If needed, further carburization and metallization of the DRI can be accomplished at the cooling zone by feeding fresh natural gas to the cooling zone, according to Reactions 14, 26, and 27.

\[
3\text{Fe}_2\text{O}_3 + 5\text{H}_2 + 2\text{CH}_4 \rightarrow \text{Fe}_3\text{C} + 9\text{H}_2\text{O} \quad \text{(Reaction 29)}
\]

\[
\text{Fe}_3\text{O}_4 + 2\text{H}_2 + \text{CH}_4 \rightarrow \text{Fe}_3\text{C} + 4\text{H}_2\text{O} \quad \text{(Reaction 30)}
\]

6.1.1.3. Reduction reactor off gas reforming—reforming of the gas utilizing the off gases from the reduction reactor: The basic schematic flowsheet of the natural gas-based direct reduction processes, which utilize off gases from the reduction reactor for reducing gas production, is shown in Figure 12. The fresh natural gas feed and reduction furnace off gases are mixed and preheated in the heat exchanger unit. These mixed gases are reformed according primarily to Reaction 18 by the supply of heat from the burning of the reduction furnace off gases, and additional fuel if needed. Cheeley (2000) reports that, for the Midrex process, burning of the furnace off gases supplies 235 Btu/ft³ energy in...
the gas reformer. A proprietary high-activity catalyst is utilized for the gas reforming Reaction 18 in these processes (Rodriguez and Scarnati 2004). Reformed gas, reducing gas mixture, produced by the reforming has the following properties (Cheeley 2000):

1) $(\%H_2 + \%CO)/(\%H_2O + \%CO_2) > 10$

2) $\%H_2/\%CO = 0.5 - 4.0$

Important disadvantages of reduction reactor off gas reforming systems can be summarized as follows (Zervas et al. 1996b; Cheeley 2000; Rodriguez and Scarnati 2004):

1) Care must be taken to operate with high % $H_2$ concentrations to lower the danger of carbon deposition of the catalyst.
2) The direct reduction processes, which utilize reduction reactor off gas reforming systems, cannot utilize high sulfur iron oxide feed stocks without prior treatment. This is due to recycling of the reduction reactor off gases to the reformer unit and danger of catalyst poisoning with high sulfur concentrations.

3) Inflexible operation conditions due to the interrelated operation of the gas reformer and reduction units.

4) The reduction reactor off gases have to be cleaned of impurities and dust contents prior to their introduction to the gas reformer unit, since the impurities and dust particles can cover the catalyst and reduce the efficiency of its operation and life time.

5) Larger gas reformer size, due to the need to process large amounts of gas.

6.1.2. Partial Oxidation Natural Gas Reforming. The partial oxidation gas reforming takes place according to the following exothermic reaction, which takes place in oxygen—or air-fired gasifier (Zervas et al. 1996 a, c; Panigrahi and Dasgupta 1999):

\[
\begin{align*}
CH_4 + \frac{1}{2} O_2 & \iff CO + 2H_2 \quad \text{(Reaction 20)} \\
CH_4 + H_2O & \iff CO_2 + 3H_2 \quad \text{(Reaction 19)} \\
CO_2 + H_2 & \iff CO + H_2O \quad \text{(Reaction 28)}
\end{align*}
\]

Reaction 28 is called a shift reaction and is generally utilized for adjustment of the hydrogen-to-carbon monoxide ratio of the reducing gas produced.

The advantages of the partial oxidation gas reforming over catalytic gas reforming can be summarized as follows (Panigrahi and Dasgupta 1999):

1) Can operate at a wider range of pressure.

2) High sulfur feed iron oxide and gas stocks can be utilized without prior treatment.

3) The reducing gases can be fed directly to the reduction reactor without scrubbing the moisture, dust and/or CO2.

4) Versatile reductant feedstocks such as fuel oil, gasoline, and naphtha can be utilized.
5) Can be installed as an alternative supply of reducing gas to the direct reduction plants operating with catalytic gas and reduction reactor off-gas reforming systems.

6) Can be adapted to most natural gas-based direct reduction processes.

6.1.3. Catalytic Gas Reforming versus Partial Oxidation Gas Reforming. Although partial oxidation gas reforming was developed earlier than catalytic gas reforming, catalytic steam gas reforming out-ranks partial oxidation gas reforming both in number and capacity of individual plants worldwide (Panigrahi and Dasgupta 1999). This is due to the operational capacity and high temperature (1260°C–1400°C) requirements of the partial oxidation gas reforming operations.

The comparison of the characteristic operational features of catalytic gas reforming and partial oxidation gas reforming is shown in Table 8 (Panigrahi and Dasgupta 1999).

The operational temperature of partial oxidation gas reforming is higher than catalytic gas reforming. This requires cooling down of the reducing gas before it is introduced to the reduction reactor. If not, partial melting or softening of the DRI in the reduction furnace might occur. This would cause buildups and sticking problems in the reactor, reducing the efficiency of the gas flow and iron yield of the process.

Partial oxidation gas reformers can operate with a wider range of reductant feed stocks, without the danger of poisoning or carbon deposition. Thus, some direct reduction plants instal partial oxidation gas reformers as backup systems to respond to the changes in the natural gas market and/or to supply reducing gas when other reformers are down.

The comparison of the reducing gas composition produced by off-gas reforming, catalytic reforming, and partial oxidation gas reforming is shown in Table 9 (Panigrahi and Dasgupta 1999). As can be seen from Table 9, the highest percentage volume H₂ composition and highest percentage volume CO and H₂ transformation in the reducing gas can be obtained by catalytic reforming.

6.2. Coal-Based Direct Reduction Processes

The coal-based direct reduction processes either utilize separate coal gasifiers for the production of reducing gases (CO, H₂) or the gasification, and reduction takes place in one single reactor. According to
Table 8. Characteristic operational features of catalytic steam reforming and partial oxidation gas reforming

<table>
<thead>
<tr>
<th>Operational features</th>
<th>Partial oxidation gas reforming</th>
<th>Catalytic gas reforming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>1260–1400°C</td>
<td>785–950°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>Can operate over a wide range of pressures.</td>
<td>Operates under low pressure and steam ratio to prevent carbon deposition.</td>
</tr>
<tr>
<td>Feedstock Utilization</td>
<td>Versatile reductant feedstock such as fuel oil, gasoline, naphtha, or natural gas can be utilized. High sulfur feed stocks can be utilized without prior treatment.</td>
<td>Commonly utilized for natural gas feed stocks. Can utilize feed stocks containing sulfur up to 1 ppm without treatment.</td>
</tr>
<tr>
<td>Steam-to-Carbon Ratios</td>
<td>Operates at very low steam ratios. This permits the usage of reducing gases without moisture removal.</td>
<td>Operates with steam-to-carbon ratios usually 1.3 to maximize the hydrogen and carbon monoxide formation.</td>
</tr>
<tr>
<td>Danger of Carbon Deposition</td>
<td>Minimal.</td>
<td>Care must be taken and operational features (temperature, pressure, and steam-to-carbon ratio) should be adjusted accordingly.</td>
</tr>
</tbody>
</table>
the nature of the coal gasification, these processes are subdivided into two processes, where gasification and reduction take place in a single reactor and processes where gasification and reduction take place in separate reactors, as shown in Table 3 and Figures 13 and 14.

6.2.1. Processes Where Gasification and Reduction Take Place in Separate Reactors. For the coal-based direct reduction processes, where the gasification and reduction take place in separate reactors, the gasification of coal can either be achieved by hydrogasification or by oxidation processes. Hydrogasification processes include reactions of hydrogen with coal to produce CH$_4$ and/or other hydrocarbons. The oxidation processes include reactions of steam and/or CO$_2$ and oxygen with coal to produce H$_2$, CO, and trace amounts of CH$_4$ (similar to partial oxidation reforming, described above). Due to high reducing gas production efficiency, oxidation processes are the main gasification process utilized for direct reduction. Further information about the gas gasification processes can be obtained from Pyrcioch (1972), Johnson (1979), Smooth and Pratt (1979), Dirksen and Linden (1963)’s work.

The oxidation gasification processes proceed according to chemical Reactions 29 and 30, which are the generalized forms of partial oxidation reactions given by Reactions 20 and 19 (Panigrahi and Dasgupta 1999;
Figure 13. Coal-based direct reduction processes according to the product and reducing-carburizing gas generation mechanisms.

Figure 14. Coal-based direct reduction processes according to unreacted coal discharging mechanisms.
Lankford et al. 1993). \((C_nH_m\) represents the hydrocarbons obtained from coal).

\[
\begin{align*}
\text{CO}_2 + \text{H}_2 & \leftrightarrow \text{CO} + \text{H}_2\text{O} & \text{(Reaction 28)} \\
C_nH_m + (n/2)\text{O}_2 & \leftrightarrow n\text{CO} + (m/2)\text{H}_2 & \text{(Reaction 29)} \\
C_nH_m + n\text{H}_2\text{O} & \leftrightarrow n\text{CO}_2 + (n + (m/2))\text{H}_2 & \text{(Reaction 30)}
\end{align*}
\]

True (1983) reports on the subdivision of coal-based processes, where the gasification and reduction take place in separate reactors, according to the product gas cleaning systems they employ, as shown in Figure 13.

For the first-generation coal gasification processes, quenching of the product (reducing gas) is required for gas cleaning. The cleaned gas has to be reheated prior to its introduction to the direct reduction reactor. Examples of first-generation coal gasification processes are: WINKER (atmospheric fluidized bed gasifier); KOPPERS TOTZEK (atmospheric entrained bed gasifier); LURGI (pressurized fix bed gasifier); TEXACO (pressurized high temperature entrained bed gasifier); and COKE OVEN (batch fixed bed gasifier) (True 1983).

For the second-generation coal gasification processes, hot product reducing gas is cleaned without the need for quenching. Due to the recovery and utilization of the reducing gas sensible heat, these processes have improved energy efficiency and lower capital costs. Examples of second-generation coal gasification processes are: KRUPP_KOPPERS (pressurized high temperature entrained bed gasifier); KRUPP_COIN (bottom blown molten bath gasifier); KHD (bottom blown molten bath gasifier); SUMITOMO (top blown molten bath gasifier); KR (side blown melter gasifier); and PLASMARED (plasma gasifer) (True 1983).

Zervas et al. (1996c) and Panigrahi and Dasgupta (1999) report the subdivision of coal-based processes, where the gasification and reduction take place in separate reactors according to discharging mechanisms of the unreacted coal (solid dry ash or slag), as shown in Figure 14. The unreacted coal is discharged from the slagging gasifiers in the form of liquid slag. The unreacted coal is discharged from the dry ash gasifiers in the form of ash.

Slagging gasifiers are utilized extensively due to their high efficiency and operational capacity advantages over dry ash gasifiers. Production rates for CO were up to three times higher with increased oxygen inputs
and higher operating temperatures, attained from slagging gasifiers. Additionally, due to high conversion rates, CH₄ production is minimized in slagging gasifiers (Zervas et al. 1996c).

6.2.1.1. Entrained bed slagging coal gasifiers versus fixed bed slagging coal gasifiers: A detailed comparison of the characteristic operation features of entrained bed slagging coal gasifiers and fixed bed slagging coal gasifiers is shown in Table 10 (Panigrahi and Dasgupta 1999; Zervas et al. 1996c).

It can be seen from Table 9 that if the reducing gas produced is to be used hot, without cooling for enrichment, shifting and removal of dust and sulfur, the entrained bed gasifiers are more economic to operate, since the hot reducing gas is produced by entrained bed gasifiers. On the other hand, the reducing gas produced by fixed bed gasifiers is a lot cooler (370°C). This is due to the transfer of sensible heat from the hot reducing gas to the fresh coal feed at the entrance of the reactor. Thus, this reducing gas is subjected to heating before it is fed to the reaction reactor. The enrichment of the gas is essential prior to heating to avoid carbon deposition and conversion of CO to CO₂ during heating.

The fixed bed slagging coal gasifiers operate in accordance with the counter-current manner. This allows the reducing gas forming reaction rates to be uniform throughout the reactor. Conversely, the entrained bed slagging coal gasifiers operate in the concurrent manner. Therefore, the reducing gas forming reaction rates vary throughout the reactor; they decrease as the reactants approach the outlet. This inhibits the complete carbon gasification and reactor size (rate of reaction rate decrease), ultimately dictating the percentage of the carbon gasified.

The entrained bed slagging coal gasifiers can successfully be operated with a wide variety of coals. However, the fixed bed slagging coal gasifiers can be successfully operated with higher-rank, non-caking coals, since caking coals would cause agglomeration problems in the shaft and lower-rank coals would produce reducing gas with higher ratios of methane and ethane (Panigrahi and Dasgupta 1999).

The oxygen requirements of the fixed bed slagging coal gasifiers are two-thirds of the oxygen requirements of the entrained bed slagging coal gasifiers. This is enabled by the utilization of sensible heat from the product (reducing gas) to heat the incoming fresh coal feed (Panigrahi and Dasgupta 1999).
<table>
<thead>
<tr>
<th>Operational features</th>
<th>Entrained bed slagging coal gasifiers</th>
<th>Fixed bed slagging coal gasifiers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material and Product Flow</strong></td>
<td>Concurrent operation</td>
<td>Counter-current operation</td>
</tr>
<tr>
<td><strong>Oxygen Requirements</strong></td>
<td>Requires more oxygen than fixed bed slagging gasifiers.</td>
<td>Requires 2/3 times less oxygen than entrained bed slagging gasifiers. This is due to utilization of sensible heat of the product gas for heating the coal before it leaves the reaction chamber.</td>
</tr>
<tr>
<td><strong>Treatment requirements of the product gas</strong></td>
<td>The product gas emerges at relatively high temperatures. It can be used directly in the reduction furnace.</td>
<td>The product gas is cooled in the upper portion of the reaction chamber. Heating of the gas is required before it is introduced to the reduction furnace. Enrichment of the gas is required prior to its heating to avoid carbon deposition and conversion of CO to CO₂ during heating.</td>
</tr>
<tr>
<td><strong>Feedstock utilization</strong></td>
<td>Can utilize a wide variety of coals.</td>
<td>Care must be taken when operating with lignite, since up to 4% total methane and ethane production can be expected. Caking coals cannot be utilized since they tend to agglomerate and cause problems in the reactor.</td>
</tr>
<tr>
<td><strong>Steam utilization</strong></td>
<td>For TEXACO gasifiers, coal slurry (ground coal + 30–40% H₂O) is used as feed. Due to high gasifier temperature and the high water injection rate, efficiency of the process is lower than the other entrained bed gasifier. For example, for SHELL gasifiers, ground coal instead of coal slurry is used as a feed.</td>
<td>Higher steam is required for efficient operation. Gas cannot be used directly due to high water content.</td>
</tr>
<tr>
<td><strong>Special operational requirements</strong></td>
<td>The reaction rate is not uniform all through the reactor; it decreases as the reactants reach the outlet. Therefore, the carbon conversion rates are highly dependent on the reactor size and residence time in the reactor.</td>
<td>Requires special mechanical assemblies in the furnace to prevent agglomeration of solids. Can operate with either slag removal or ash removal, depending on the oxygen-to-coal and steam-to-coal ratios.</td>
</tr>
<tr>
<td><strong>Auxiliary plant requirements</strong></td>
<td>No waste liquor treatment plants are required.</td>
<td>Waste liquor treatment plants are required for tar recovery.</td>
</tr>
</tbody>
</table>
6.2.2. Processes Where Gasification and Reduction Takes Place in a Single Reactor. Coal is introduced to the reduction reactor along with the iron oxide and flux (if needed) materials. Inside the gasification/reduction reactor, the following reactions take place (Ghosh and Tiwari 1970; Rao 1971; Fruehan 1977; Srinivasan and Lahiri 1977; Seaton et al. 1983; Abraham and Ghosh 1979; Ajersch 1987; Zervas et al. 1996b):

1) Thermal decomposition, gasification of coal reactions

\[ \text{Coal} \rightarrow \text{CO}, \text{CO}_2, \text{H}_2, \text{N}_2, \text{C}_n\text{H}_m, \text{C} \quad \text{(Reaction 31)} \]

\[ \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \quad \text{(Reaction 32)} \]

\[ \text{C} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} \quad \text{(Reaction 33)} \]

And Reactions 18, 20, 23, and 24

2) Iron oxides reduction and carburization reactions (Reactions 1–17)

3) Slag-forming reactions

Due to the complexity of the slag-forming reactions and heterogeneity of the system, only the basic, predictable reactions will be listed in this article.

\[ \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \quad \text{(Reaction 34)} \]

\[ \text{CaO} + \text{SiO}_2 \rightarrow \text{CaSiO}_3 \quad \text{(Reaction 35)} \]

\[ \text{SiO}_2 + 2\text{C} \rightarrow \text{Si} + 2\text{CO} \quad \text{(Reaction 36)} \]

\[ \text{FeO} + \text{SiO}_2 \rightarrow \text{FeSiO}_3 \quad \text{(Reaction 37)} \]

\[ \text{FeSiO}_3 + \text{CaO} \rightarrow \text{CaSiO}_3 + \text{FeO} \quad \text{(Reaction 38)} \]

\[ \text{FeS} + \text{CaO} + \text{C} \rightarrow \text{CaS} + \text{FeO} + \text{CO} \quad \text{(Reaction 39)} \]

Kinetics of these reactions have been studied by Ghosh and Tiwari (1970), Rao (1971), Fruehan (1977), Srinivasan and Lahiri (1977), Seaton et al. (1983), Abraham and Ghosh (1979) and Ajersch (1987) for determination of the rate-controlling steps to improve the efficiency of the process. Wustite (FeO) reduction to iron (Fe), the Boudouard
reaction (Reaction 34), heat transfer effects, and diffusion of reactants and products were found to affect the kinetics and efficiency of the process.

The coals with high ash fusion temperature, high reactivity, and small sulfur contaminants (less than 1%) are preferred for these processes. They can be fed to the system as fines or agglomerated along with the iron oxides and additives. The agglomeration of all ingredients helps to enhance the kinetics of the reduction reactions (Goksel 1977; Goksel et al. 1988; Weiss et al. 1987). This is due to the fine dispersion of the reacting materials in the system. The close contact of the reacting materials and availability of a large number of reacting sites enhances the kinetics of the chemical reactions (direct and indirect reduction, and slag-forming reactions (see Figure 1). Also, internal gas generation and small gas diffusion distances enhance the indirect reduction reactions (Agrawal et al. 2000; Haque and Ray 1995; Nascimento et al. 1998; Mourao and Capacchi 1996).

The major problem faced with coal-based processes where gasification and reduction takes place in a single reactor is the sticking of the semi-fluid ore and coal fines to the hot walls of the reduction chamber. This problem can be minimized by the utilization of feed stocks, which can resist degradation during reduction (Panagrahi and Dasgupta 1999).

Panigrahi and Dasgupta (1999) report that improved performance can be achieved for the coal-based processes where the gasification and reduction take place in a single reactor by the utilization of lower rank (sub-bituminous and lignite) coals. For example, when operating with anthracite coal, stable operation can be attained at temperatures above 1160°C. When operating with bituminous coal, stable operation can be attained at reduced feed rates and low degrees of metallization. However, throughput can be increased by 35% when operating with lower-rank coals.

7. WORLD-WIDE DRI PRODUCTION

The annual world DRI production (Mton) since 1970 is shown in Figure 15 (Midrex Technologies Inc. 2004; Shawcross 2004). The percentage of the DRI produced by natural gas-based processes (utilizes reformed natural gas as a reducing agent) and the percentage of the DRI produced by coal-based processes (utilizes carbon bearing materials
as a source of reducing agent) are shown in Figures 16 and 17, respectively (Midrex Technologies Inc. 2004). It can be seen from Figure 15 that the continuous increase in the production was interrupted at
1982–83 and 2001. The 1982–83 interruption was due to the recession and the 2001 interruption was due to fluctuating natural gas and steel prices (see Figure 15) (Midrex Technologies Inc. 2004; Balcerek 2003). In 2001, many of the natural gas-based direct reduction plants had experienced short-term shut downs until natural gas prices stabilized. For example, the Ispat International DRI module at Hamburg, Stahlwerhe, was shut down in April and started to re-operate when natural gas prices were lowered 30% in October 2001 (Anonymous 2001a).

The highest increase in the production was observed in 2000, when the production increased 11.8% with respect to 1999 (Anonymous, 2001a). This was due to: 1) decreasing scrap quality and reserves; 2) increasing scrap prices; and 3) startup of 20 direct reduction plants with a total capacity of 20 million tons worldwide, which were built between 1997 and 2000 (Tanigaki and Kobayashi 2000).

The predicted production capacity for 2006 annual DRI is also shown in Figure 15 (Anonymous 2001b). This increase in production is expected to be mostly accomplished with growth of coal-based direct reduction processes (see Figures 16 and 17) (Midrex Technologies Inc. 2002, 2003, 2004; Shawcross 2004). An example of this type of increase is the sudden 35% growth of the coal-based DRI production capacity in India during 2003 (Balcerek 2003).
8. CONSUMERS OF DRI

The solid DRI can be utilized in:

1) Electric arc furnaces along with scrap for steel production.
2) Ferrous foundry operations as a new iron unit charge.
3) Electric arc furnaces, foundry cupolas, and basic oxygen furnaces as coolant.
4) Blast furnaces to increase throughput.

8.1. Utilization of DRI in the Electric Arc Furnace, Along With Scrap, For Steel Production

Solid DRI is mostly consumed by electric arc furnaces along with scrap for melting, refining, and conclusively molten steel production purposes, as shown in Figure 18. Comparison of the DRI utilization with scrap utilization in the electric arc furnace is shown in Table 11 (Henderson 1980; Zervas et al. 1996a; Jones 2004; Klemm and Stercken 1998).

An electric arc furnace is a batch-operating reactor where DRI and/or scrap is melted, refined, de-slagged, and tapped into a ladle. The energy required for melting and refining is supplied by electrical energy through graphite electrodes and by chemical energy through exothermic oxidation reactions. The graphite electrodes are dipped into the charge, causing electric arcs to be produced between the electrode and the bath, providing 50–60% of the energy required. After melting, the refining and removal of aluminum, silicon, manganese, phosphorus, and carbon is accomplished by exothermic oxidation reactions (provides 40–50% of the energy required in the process). Since these elements
Table 11. Comparison of DRI utilization with scrap utilization in the electric arc furnace

<table>
<thead>
<tr>
<th>Steel scrap</th>
<th>DRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Unknown (or not very well known) chemical composition</td>
<td>• Operating with well-known chemical composition and low content of metallic residuals (Cu, Ni, Cr, Mo, Sn)</td>
</tr>
<tr>
<td>• Hard to achieve uniform melting</td>
<td>• Melts more uniformly without preparation when compared with steel scrap</td>
</tr>
<tr>
<td>• Must be layered and prepared according to size and density to promote rapid and uniform melting along with cave-in protection</td>
<td>• Utilization leads to the protection of the side walls and roof of the furnace from the electric arcs due to uniform melting</td>
</tr>
<tr>
<td>• Non-uniform melting of the slag retards the process and its efficiency</td>
<td>• No danger of cave-ins and electrode breakage with impact due to more uniform and finer sizing of the DRI when compared with steel scrap</td>
</tr>
<tr>
<td>• Danger of scrap cave-ins and consequent electrode breakage in electric arc furnace</td>
<td>• Better control of molten steel quality and composition can be achieved</td>
</tr>
<tr>
<td>• Higher energy and/or fuel consumption, longer melting time when compared with DRI</td>
<td>• After all of the charge is melted and flat bath conditions are obtained, foamy slag production (see Reactions 1–3 in Section 4) and consequent protection of furnace walls and the roof from the electric arc and longer furnace refractory life can be achieved by its utilization</td>
</tr>
<tr>
<td>• Can only be charged to the electric arc furnace batch-wise by opening the entire roof of the furnace. After the melting of the first load, the roof has to be re-opened to load more material to balance the charge. This results in delays and considerable heat loss during the operation (Jones [2004] reports that the energy loss each time the furnace roof opened is 10–20 KWh/ton of DRI)</td>
<td>• Self-stirring of the slag (see Reactions 1–3 in Section 4) in the bath can also be achieved by its utilization. This improves the reaction kinetics by renewing the slag/metal reaction interfaces</td>
</tr>
<tr>
<td>• Can be charged continuously to the electric arc furnace from a small opening on the roof of the furnace. This operation enables charging of the DRI at the same rate that its being melted, which results in more rapid and efficient melting, eliminating the heat loss from opening the entire roof of the furnace.</td>
<td></td>
</tr>
</tbody>
</table>
have a higher affinity for oxygen than carbon, they preferentially react with the oxygen supplied through an oxygen lance and form oxides. These oxides float out of the steel into the slag level. The slag formed is removed from the furnace by the de-sludging stage to prevent reversion of refining reactions. After de-slagging, the molten steel produced is tapped into the ladles for easy transfer (Jones 2004).

The charging of the scrap into the furnace is accomplished by swinging the roof and the electrodes to the side, allowing the crane to move a full bucket of scrap into the furnace. After charging, the roof and electrodes swing back and are lowered. On the other hand, the DRI is charged to the furnace through an opening in the roof (Jones 2004).

The efficiency of the electric arc furnace operation described above can be improved by the utilization of DRI according to the following aspects (Jones 2004) (see Table 11):

1) Utilization of DRI instead of scrap allows operating with a better-known chemical compositions and low content of metallic residuals (Cu, Ni, Cr, Mo, Sn).

2) Unlike scrap, DRI can be charged into the electric arc furnace throughout an opening on the roof. The furnace power is not turned off and the roof is not swung to the other side for charging. The furnace atmosphere stabilizes faster; thus, the arc becomes more stable and the average power input increases.

3) Prior to scrap charging into the electric arc furnace, the scrap must be layered and prepared according to its size and density to promote rapid and uniform melting along with cave-in protection. Non-uniform melting of the scrap retards the process and its efficiency. The scrap cave-ins can be prevented by placing heavy pieces away from the electrodes to protect them from breaking. On the other hand, DRI melts uniformly without the need for preparation. This uniform melting provides protection on the side walls and roof of the furnace from electric arcs. Due to uniform sizing of the DRI, there is no danger of cave-ins that would lead to electrode breakage with impact.

4) DRI has higher bulk density than most of the scrap utilized in the electric arc furnace operations (Scarnati et al. 1999). Therefore, its utilization in the charge or as charge reduces the back-charging operations, improving the economics of the operation. Back charging is charging additional material (scrap and/or DRI), after the previous
charge is melted, but still in the furnace to make up for the required amount of material in the furnace. As the number of charging or the time taken for charging the furnace is reduced, the productivity of the furnace increases. During charging, the furnace does not have any power on and therefore there is no melting. In the same manner, DRI can also be utilized along with scrap to densify the charge in the scrap charge bucket (Pietsch 1978a).

5) Close control of the molten steel quality and composition can be accomplished by the utilization of DRI. Most of the electric arc furnaces operate with DRI to scrap ratio 45% (Zervas et al. 1996b). However, the QASCO’s electric arc furnace operates with 95% DRI charge (the highest ratio in the steel producing world) to be able to closely control the quality of the steel they produce (Takla 1998).

6) Once all the charge material is melted, flat melt (no foaming and bubbling) conditions are obtained. In this condition, the side walls and roof of the furnace are exposed to electric arc radiations. These radiations can be reduced by decreasing the voltage or by the formation of foaming slag (Pietsch 1978a). The voltage decrease is not preferred due to increased residence time in the furnace. However, formation of foamy slag is preferential, since a greater amount of energy is retained and transferred (greater energy efficiency) by the slag in the bath. The foamy slag formation is promoted by the utilization of higher percentages of DRI in the charge.

8.2. Utilization of DRI in Ferrous Foundry Operations as New Iron Unit Charge

Starting in the early 1960s, there has been a great deal of research interest in utilization of DRI as new iron units for the charge in the ferrous foundry operations instead of pig iron and scrap. The main incentives behind this are as follows (Pena and Radke 1971; Bonestell and True 1983; Henderson 1980; Pietsch 1978a; Pietsch 1976b, 1976c; Grumbrecht et al. 1975; Wenzel et al. 1975; Geck and Maschlanka 1976):

1) DRI has more dependable and stabilized market structure when compared with steel scrap.

2) DRI is easily adaptable and versatile for continuous charging operations.
3) Advanced phosphorus and sulfur removal can be achieved when utilizing DRI if sufficient slag basicity is attained by the addition of lime.

4) Unlike steel scrap, DRI has a lower concentration of tramp (residual) elements, which cause problems during casting. Some of the important production advantages that can be achieved by the utilization of DRI can be summarized as follows (Pietsch 1978a):

   a) When producing gray cast iron, it is important to have low titanium and aluminum concentrations. The presence of these tramp elements promotes the formation of gas bubbles, which produces pin holes.

   b) When producing iron with nodular graphite, it is important to have low titanium, aluminum, antimony, bismuth, zirconium, tin, lead, and arsenic concentrations. Presence of these tramp elements promotes the formation of flake and vermicular graphite instead of nodular graphite in the cast iron structure.

   c) When producing ductile iron, its chromium and manganese content must be kept to a minimum to account for their chill-inducing effects.

   d) When producing gray and ductile iron, the chromium, vanadium, molybdenum, copper, nickel, tin, and boron concentrations should be kept at a minimum to inhibit carbide formation.

Although DRI utilization in the ferrous foundry melt furnaces has the advantages stated above, it has not gone into general use. The main reasons behind this can be summarized as follows (Henderson 1980; Burlingame 1999):

1) Unlike pig iron and steel scrap, DRI contains considerable amounts of gangue and iron oxide in its structure (see Table 2). This reduces the efficiency of the melting; increases the fuel, energy, and operation time requirements; and causes problems during melting, tapping, and de-slagging.

2) The iron oxide present in DRI is reduced by the gasification of carbon (which was in the form of C or Fe₃C), also present in the structure. These reactions produce foamy slag and stirring in the bath. Although foamy slag production and stirring of the bath are advantageous in the electric arc furnace melting, they cause problems in induction, cupola, and reverberatory furnace melting operations.
3) Due to the high porosity of the DRI structure, some of the metallic iron oxidizes to wustite (FeO) by oxygen in the air or oxygen lanced or combustion gases, etc. This wustite that is formed usually cannot be recovered and is lost in the slag.

Contrary to the operational difficulties stated above, some ferrous foundry operators still utilize 10–15% DRI as new iron source (Henderson 1980). These DRI feed stocks utilized have high-quality requirements, including a high degree of metallization and low gangue and residual element content to minimize the operational problems.

8.3. Utilization of DRI in Electric Arc Furnaces, Foundry Cupolas, and Basic Oxygen Furnaces as Coolant

DRI is added to the electric arc furnaces, foundry cupolas, and basic oxygen furnaces to lower the temperature increase caused by the vigorous exothermic reactions.

The chemical composition, particle size distribution, and apparent and bulk density of the DRI are important for its effective utilization as a coolant in these applications. For example, if it is utilized in basic oxygen furnaces, its density and the size distribution (larger than 3 mm) is important for determining the effectiveness of its penetration through the thick slag layer, and to avoid carry-over (Pena and Radke 1971; Bonestell and True 1983). Or, if it has high silica content, the amount of lime consumption increases. This consequently increases the amount of iron being lost in the slag.

In addition, DRI also is occasionally utilized to adjust the carbon-to-silicon ratio in electric arc furnaces, foundry cupolas, and basic oxygen furnaces.

8.4. Utilization of DRI in Blast Furnaces to Increase Throughput

DRI is often utilized in blast furnaces to increase production to meet market demands, and to compensate production in the case of short-term coke oven failure. Continuous utilization of DRI in blast furnaces lowers the coke consumption and, in conjunction, lowers the cost per ton of iron; since the amount of coke required for melting is three times less than the amount of coke required for smelting (Schriefer 1995). In addition, it also improves the daily production, decreases the variation in the hot metal composition, and decreases the amount of flux required...
For the DRI to be used in blast furnaces, it has to have an iron content of more than 68% and, correspondingly, the gangue should be less than 3% (Pietsch, 1978b). Petry (1996) reported that more than 50% of the DRI produced was utilized in blast furnaces in 1994.

9. DRI QUALITY

The efficiency of the electric arc furnace operation is defined by the following factors: 1) electric consumption; 2) melting time required; 3) electrode consumption; and 4) refractory life. The operational performance of these factors is highly dependent on the DRI feed quality. However, there still has not been any published specification for DRI quality.

DRI quality is defined by the following factors:

1) The amount of fines

This affects the energy efficiency of the electric arc furnace operation and may cause contaminations of the electrical parts. It also causes problems in handling and loading the DRI.

2) The amount of carbon

The amount of carbon in the DRI is controlled between 1–2.5 wt%. It has been reported by Myers (2003) that more than 90% of the carbon present is utilized for the following reactions, if sufficient oxygen is supplied:

1) Endothermic Reaction 11, where iron oxide and carbon reacts to form iron: More than 90 wt% of the FeO present in the DRI gets reduced by this reaction (Myers 2003). It was reported by Metius (2000) that for each 1.0% Fe in the form of FeO present in the DRI theoretically requires wt 0.215% C to reduce it.

\[
\text{FeO} + \text{C} \rightarrow \text{Fe} + \text{CO} \quad (\text{Reaction 11})
\]

2) Endothermic Reaction 40, generation of carbon monoxide to increase iron recovery by reduction of FeO present:

\[
\text{CO}_2 + \text{C} \rightarrow 2\text{CO} \quad (\text{Reaction 40})
\]

3) Exothermic Reaction 33, oxidation of carbon:

\[
\text{C} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO} \quad (\text{Reaction 33})
\]

This oxidation reaction (Reaction 33) replaces a considerable amount of electric energy required for melting in the electric arc
furnace with chemical energy. If the carbon in DRI is in the form of iron carbide, more chemical energy can be obtained by its oxidation. In addition, oxidation of carbon produces CO, which provides stirring and slag foaming in the electric arc furnace bath. Slag foaming in the electric arc furnace increases the thermal efficiency, protects the furnace walls and roof from the intense electric arcs, and prevents nitrogen and hydrogen from being exposed to the arc where it can dissolve in to the steel. Stirring of the bath improves the reaction kinetics by renewing the slag/metal reaction interfaces (Anderson 2002; Metius 2000; Giguere 2000; Myers 2003; Jones 2004).

3) The amount of iron oxide and metallic iron

The amount of iron oxide present determines the amount of extra energy required for reduction. Leckie (1982) reports that if the metallization is not completed in the direct reduction process, theoretically 41 MJ/ton of energy is required to reduce 1% Fe present as wustite (FeO) into metallic iron in an electric arc furnace (when metallization is between 91–95%). Thus, the higher the metallization of the DRI, the lower the energy required to reduce wustite (FeO) present in the structure.

4) The amount of slag

This amount determines the extra amount of energy and residence time required to melt it. However, its presence also substitutes for slag-building agents in the electric arc furnace burden (Poveromo and Swanson 1999).

10. DRI HANDLING, STORAGE, AND TRANSPORTATION

The handling, storage, and transportation requirements of DRI are dependent on the physical degradation and/or chemical stability properties. Due to its porous morphology, DRI can re-oxidize or self-heat to the point of ignition. The re-oxidation tendency of the DRI produced at QASCO (Qatar Steel Company Ltd.) plant is shown in Figure 19 (Takla 1998). The oxidation reaction is an exothermic reaction. When it is coupled with the low thermal conductivity of the DRI, it is possible for DRI to self-heat itself to the point of ignition (Birks and Alabi 1986). To prevent this from happening during the handling, storage, and transportation of solid DRI, ventilation and gas sealing is required (Hunter 1999). Further information about the storage and shipping precautions of DRI have been reported by
The chemical and physical stability of the DRI is dependent on the following factors (Lankford et al. 1993; Hunter 1999; Pietsch 1976a; Birks and Alabi 1986, Parrage et al. (1994), and Hunter (1997).

The chemical and physical stability of the DRI is dependent on the following factors (Lankford et al. 1993; Hunter 1999; Pietsch 1976a; Birks and Alabi 1986):

1) **Mineralogy or the origin of the iron oxide**
   The mineralogy or the origin of the iron oxide determines the reactivity and reducibility of the ore.

2) **Reduction temperature and residence time**
   Steffen and Lungen (2004) and Lankford et al. (1993) report that the stability of DRI to re-oxidation and self-ignition can be improved by increasing the working temperature and residence time during reduction. As the reduction temperature and residence time increases, the particles start to soften and grains start to fuse. This consequently reduces the internal surface area by producing larger but fewer pores (Hunter 1999; Pietsch 1976a).

3) **Reducing agent composition**
   The reducing gas composition determines the efficiency of the reduction and the formation of stable carbides.
4) Surface area (degree of porosity) exposed to weathering conditions

The oxidation tendency of the DRI is proportional to the surface area exposed to weathering conditions. The DRI is usually briquetted into hot briquetted iron (HBI) or cold briquetted iron (cold-bonded iron; CBI) to reduce the surface area being exposed to weathering conditions. HBI is produced from DRI fines and contains less carbon than DRI (average 1.5–1.8% C) since it is difficult to recover or replace the carbon burnt off in the briquetting furnace while maintaining the required temperature (Metius 2000). Some of the important properties of the HBI are shown in Table 12 (Pietsch 1978a; Metius 2000; Schutze 2002).

CBI is produced from DRI fines that are too small to be used in the granular form of hot briquetting. It has lower iron content than DRI and HBI. During briquetting, coke, alloying materials, and deoxidizing agents are used as binders. CBI is mostly used in blast furnaces to increase the throughput, to continue operation if the coke oven is down, to improve the hot metal quality, and to reduce the coke requirement of the blast furnace.

The comparison of the important properties of the DRI, HBI, and CBI are shown in Table 13 (Pietsch 1978a; Metius 2000; Schutze 2002; Hunter 1997; Parrage et al. 1994).

5) Age

The re-oxidizing tendency of DRI decreases with increasing age (Hunter 1999; Ninneman 1997). The freshly produced DRI has a higher tendency to re-oxidize then the aged DRI. After the formation of oxidized coating on the DRI at first exposure to the oxidizing atmosphere, further oxidation is inhibited (Pietsch 1976a). To prevent

<table>
<thead>
<tr>
<th>Property</th>
<th>HBI values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Density</td>
<td>4.9–5.5 g/cm³</td>
</tr>
<tr>
<td>Bulk Density</td>
<td>2.4–2.8 ton/m³</td>
</tr>
<tr>
<td>Average Weight</td>
<td>500–600 g</td>
</tr>
<tr>
<td>Average Size</td>
<td>106 × 48 × 32 mm</td>
</tr>
<tr>
<td>Carbon Content</td>
<td>1.0–1.3 wt%</td>
</tr>
<tr>
<td>Metallic Iron</td>
<td>84% min</td>
</tr>
<tr>
<td>Total Iron</td>
<td>90–94%</td>
</tr>
<tr>
<td>Degree of Metallization</td>
<td>90–95%</td>
</tr>
</tbody>
</table>
Table 13. Comparison of some important properties of DRI, HBI, and CBI

<table>
<thead>
<tr>
<th>Properties</th>
<th>DRI</th>
<th>HBI</th>
<th>CBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumers</td>
<td>Adjacent melt-shops or electric arc furnaces to DRI production plant</td>
<td>Electric arc furnaces, foundry cupolas, basic oxygen furnaces, and blast furnaces</td>
<td>Mostly blast furnaces</td>
</tr>
<tr>
<td>Carbon content</td>
<td>Higher than HBI</td>
<td>Lower than DRI</td>
<td>Higher than HBI can be adjusted with the utilization of binders</td>
</tr>
<tr>
<td>Porosity, specific surface area</td>
<td>Higher than HBI and CBI</td>
<td>Lower than DRI</td>
<td>Lower than DRI. Higher than HBI</td>
</tr>
<tr>
<td>Density, bulk density</td>
<td>Lower than HBI and CBI</td>
<td>Higher than DRI and CBI</td>
<td>Lower than DRI and HBI</td>
</tr>
<tr>
<td>Degree of metallization</td>
<td>90–95% Approximately the same as the HBI</td>
<td>90–95% Approximately the same as the DRI</td>
<td>Lower than DRI and HBI</td>
</tr>
<tr>
<td>Percent metallic iron</td>
<td>~85% Approximately the same as the HBI</td>
<td>~85% Approximately the same as the DRI</td>
<td>~60–65% Lower than DRI and HBI</td>
</tr>
<tr>
<td>Chemical stability (re-oxidation characteristics)</td>
<td>DRI produced by natural gas-based processes—Special precautions have to be taken to prevent the re-oxidation DRI produced by coal-based processes—More stable than DRI produced by natural gas-based processes, but still need special precautions to prevent re-oxidation</td>
<td>DRI that has been briquetted at temperatures of &gt;650°C and has reached the apparent density 5 g/cm³ is generally more stable. There is Minimal loss metallization even after long-time storage</td>
<td>More stable than DRI</td>
</tr>
<tr>
<td>Production of fines during handling and shipping</td>
<td>Higher than HBI</td>
<td>Little production of fines. Handling is similar to scrap.</td>
<td>Lower than DRI and higher than HBI</td>
</tr>
<tr>
<td>Moisture saturation</td>
<td>~12–14%</td>
<td>Lower than DRI ~3%</td>
<td>Lower than DRI, higher than HBI</td>
</tr>
</tbody>
</table>
first oxidation, there has been a considerable amount of research done
to find coatings that could be applied to the DRI, without affecting the
steelmaking process.

6) Previous history of handling and exposure
The amount of dust formed during previous handling is an important factor for accelerating the rusting and self-ignition. The metal
dust does not ignite as easily as the fuel dust. However, under certain
conditions (high density dust and heat supply) it ignites faster than
the compacted DRI. In addition, DRI dust rusts easily due to its fine
size.

11. SUMMARY
The blast furnace processes are still the primary ironmaking technology. The disadvantages inherent to this process lead to the development of
alternative processes such as smelting reduction processes, mini-blast
furnace process, and direct reduction processes. Blast furnace, mini-
blast furnace, and smelting reduction processes include reduction and
smelting of the iron oxide feed stocks producing slag-free pig iron. On
the other hand, direct reduction processes include solid state reduction
of iron oxide feed stocks producing, DRI. DRI is a solid, highly metal-
lized structure, which still contains slag. The slag separation from the
metal cannot be accomplished in direct reduction processes due to lack
of melting. DRI can be utilized in electric arc steelmaking, ferrous foun-
dry operations, and blast furnaces. Increasing demand on electric arc
steelmaking, and the need for steelmaking feed materials with well-
known chemical composition, enables the direct reduction processes to
gain importance over the past century. Hence, the advantages of the
DRI utilization can be summarized as follows:

1) Unlike coke (utilized for blast furnace pig ironmaking) direct
reduction processes utilize low-cost, widely available fuel and/or
reducing agent feed stocks like hydrocarbon gases (hydrogen,
carbon monoxide, carbon dioxide, methane) and coal-bearing
materials (coal, coke breeze).
2) The utilization of DRI in electric arc furnaces instead of scrap
allows easier and cheaper production of high-quality steel. This is
due to the consistent well-known chemical composition and low
content of metallic residuals (Cu, Ni, Cr, Mo, Sn) of DRI.
3) The melting of DRI requires less energy and more uniform heating cycle than scrap in the electric arc furnace.
4) The DRI has higher bulk density than most of the scrap utilized in the electric arc furnace steelmaking.
5) During melting, the following operation advantages can be obtained by the utilization of direct reduced iron instead of scrap: 1) the electric arc furnace wall and roof protection (by foamy slag formation); 2) thermal and kinetic (by bath self-stirring) efficiency increase.
6) The DRI can be charged continuously to the electric arc furnace. Scrap has to be charged with batch operations.
7) The utilization of DRI in foundry operations as inocculants improves the properties of the cast iron.
8) The efficiency and throughput of the blast furnace can be improved by the utilization of DRI.
9) The coke and flux consumption of the blast furnace process can also be reduced by the utilization of DRI.
10) The direct reduction plants can be operated with a flexible range of different capacities. This is in contrast to the blast furnace, where thermal and chemical efficiency of the operation can only be achieved at high capacities. This inhibits the ability of blast furnace operations to adjust to market fluctuations.
11) The direct reduction processes can be expanded incrementally with minimal investment risks.
12) The DRI has a more predictable price structure when compared with scrap.

For DRI production, two possible routes, natural gas-based and coal-based, are available. The natural gas-based processes utilize hydrocarbon gases such as methane, hydrogen, and carbon monoxide for iron oxide reduction and carburization. On the other hand, coal-based processes utilize carbon-bearing materials for iron oxide reduction and carburization. Worldwide, over 90% of the DRI production is made through natural gas-based processes. However, at locations where natural gas utilization is expensive, coal-based processes are gaining importance and more coal-based processes are being commercialized at these locations.

Natural gas-based direct reduction processes can be subdivided into two categories, according to the mechanisms they utilize for reducing and carburizing gas generation, such as catalytic and partial oxidation gas reforming. Coal-based processes can also be subdivided into two
categories, according to the mechanisms they utilize for reducing and carburizing gas generation, such as processes that utilize coal gasification and processes where coal gasification and iron oxide reduction take place in a single reactor.

Natural gas-based processes utilize vertical shaft, retort, and fluidized bed furnaces for reduction reactions. On the other hand, coal-based processes utilize rotary kiln, fluidized bed, vertical shaft, multiple hearth, and rotary hearth furnaces for reduction reactions. Pellets and lump ore are usually beneficiated in vertical shaft, retort, and rotary kiln furnaces. Fine ore is beneficiated in fluidized bed reactors. Green balls composed of iron oxides, reductant, flux, and binder are beneficiated in rotary hearth and multiple hearth furnaces.

The quality of the DRI produced by these processes is highly dependent on the raw materials utilized, since throughout the processes only oxygen inherent to the iron oxide feed stocks is removed from the system and gangue minerals remain in the structure. In addition, the reduction reactor being utilized dictates the physical and reduction characteristics of the iron oxide feed stocks required for the processes.

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