Premium Quality DRI Products from ENERGIRON

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1. Abstract

This paper focuses on the characteristics that distinguish the High-Carbon DRI produced by the ENERGIRON ZR process as compared to conventional, lower carbon DRI. High-C DRI can be produced in any of three forms, High-Carbon Cold DRI (High-C CDRI), High-Carbon Hot DRI (High-C HDRI) and the novel High-C-HBI. As analyzed in this paper, High-C DRI is an *innovative* product that has been routinely produced for nearly 20 years, and whose benefits in the EAF have been widely proven as a *reliable* source of premium metallic material. In terms of *sustainability*, the High-C DRI/HBI has a larger impact in terms of reduction of CO_2 emissions per ton of liquid steel (tLS) either when used in the EAF, or as a metallized burden to the BF. It additionally presents easier and *safer* procedures during handling and storage because of the higher iron carbide (Fe_3C) content (higher than 50% of DRI composition), which makes this product more stable.

2. DRI Products

DRI is a high Fe, low residual metallic material for producing high quality iron and steel products in a wide variety of furnaces. DRI is produced by the direct reduction of iron ore by hot reducing gases, namely hydrogen (H_2) and carbon monoxide (CO), which are generated from different energy sources:

- Natural gas reforming
- Coke oven gas
- Syngas from coal gasification
- Hydrogen from hydrocarbons or from renewable energy sources

For the case of the ENERGIRON process, the natural gas reforming takes place "*in-situ*" while in contact with the metallic iron inside the direct reduction reactor.

DRI can be produced in three different ways:

- Cold DRI (CDRI); produced by cooling the DRI from the DR reactor reduction section in the lower cone, or in external cooler, and discharged at about 50°C. It is typically used for captive steelmaking facilities or transported from a remote location to operating meltshops. Normally used for continuous charging to EAF. Classified as DRI (B) as per the International Maritime Organization (IMO).

- <u>Hot DRI (HDRI)</u>; directly discharged from a hot DRI reactor and transported to adjacent, captive EAF, fed at about 600°C. The conventional transport media used by ENERGIRON DR plants is the HYTEMP® system, with nearly 20 years of proven reliability.

- <u>Hot briquetted iron (HBI)</u>; DRI that is compacted at high temperature. It is normally produced by merchant DRI plants since it provides the best performances with regards to stability vs. re-oxidation and fines generation. HBI is used for various steelmaking facilities, including EAF, BF and BOF. Classified as DRI (A) as per the International Maritime Organization (IMO).

Although the ENERGIRON DR process can produce any type of DRI, related to % carbon content, the unique and differentiating feature of this technology is the production of High-C DRI with controlled carbon content, typically from ~1.5% - 4.5%. Table 1 shows typical DRI characteristics for this evolutionary product.

Figure 1. CDRI, HDRI, HBI

Table 1. Unique High-Carbon DRI products from ENERGIRON ZR technology

ENERGIRON HIGH-CARBON DRI			
	High-C CDRI	High-C HDRI	High-C HBI
Metallization	**94%**	**94%**	**94%**
Carbon	**4.0%**	**4.0%**	**3.5%**
Fe°	84.9%	84.9%	85.3%
Fetot	90,3%	90.3%	90,8%
Fe$_3$C	**55.1%**	**55.1%**	**49.2%**
Gangue	4.1%	4.1%	4.2%
Apparent density (g/cm^3) [(1)]	3.4 – 3.6	3.4 – 3.6	4.8 - 5,0 [(2)]
Bulk density (g/cm^3)	1.6 – 1,9	1.6 – 1.9	2.5 – 3.3
Porosity (%)	50 – 60	50 – 60	10 – 15
Typical size (mm)	4 - 20	4 - 20	~30x50x110
DRI temperature	~50°C	HDRI: ≥700°C @ reactor discharge ~600°C @ EAF charge	~50°C

[(1)] Apparent density related to the mass and volume of a single piece of DRI, including all porosity (open+closed) in the considered volume.
[(2)] Depending on the %C content in the HBI.

High-C DRI, as further detailed in point 3 below, is more stable than conventional DRI, normally produced by other DR technologies. The conventional DRI is normally more susceptible to re-oxidation, therefore requiring a further step of aging or "passivation". This better behavior of High-C CDRI has been largely demonstrated in

actual plant operations, such as Ternium Mexico, Nucor Louisiana, Suez Steel Company in Egypt and ESI#3 Abu Dhabi (Figure 2). However, some precautions during handling, storage and transport should be taken into account, particularly with CDRI. Since this is a highly porous material, contact with water should be prevented to avoid any possibility of material re-oxidation or risky operations in the EAF (Table 2).

In general, DRI is not considered as a scrap substitute but rather as a source of clean iron units that can be used to supplement and enhance the scrap charge for the production of high quality steel products. DRI matches pig iron in production of high quality steel due to its value as a virgin metallic source, as indicated in Figure 3 below.

Figure 2. Storage of High-Carbon DRI

High-C DRI in open yard; not screened, not subject to passivation. 3M5-ZR plant, Ternium Monterrey
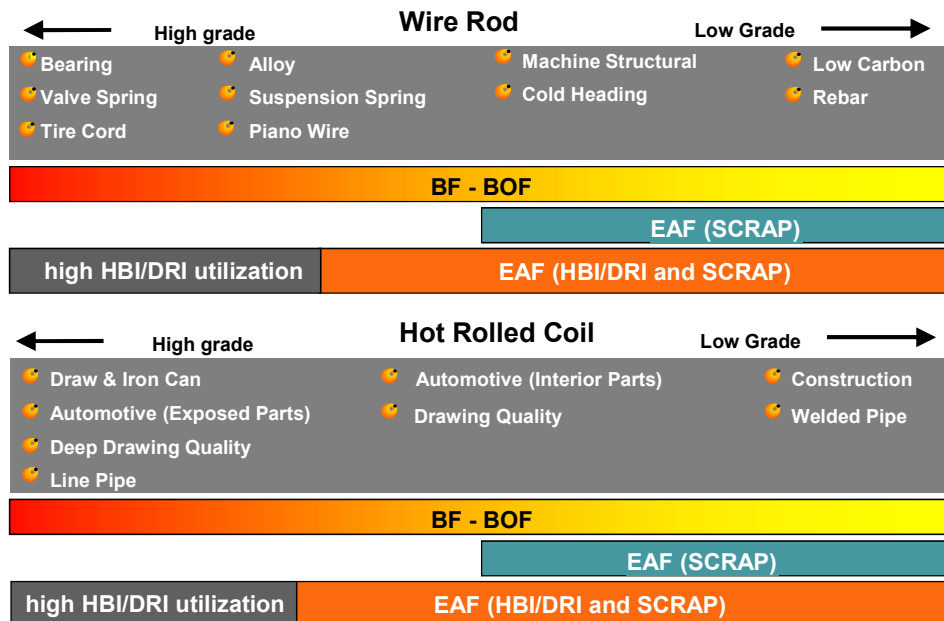
High-C DRI in silos and open yard; not screened, not subject to passivation. Emirates Steel Micromodule-ZR plant, Abu Dhabi.

Table 2. Handling storage and transport of High-Carbon DRI products

Product	Transport	Handling/storage
High-Carbon CDRI	**Inland**: trucks/rail gondola cars may be open. Cover to avoid water intake in raining locations. **River**: covered barges. **Ocean**: as per IMO [schedule DRI(B)]	**Handling**: conventional low-cost handling systems. Minimize transfer points, free fall heights, use of mobile equipment. **Storage**: Stockpiling in open yard. Shedding recommended to prevent water intake with raining/snowing.
High-Carbon HDRI	HYTEMP® system, which is completely enclosed and isolated.	Direct feeding to buffer bins/EAF charging.
High-Carbon HBI/std. HBI	No special provisions for inland or overseas transport [IMO schedule DRI (A)].	No special provision fo storage in open yard.

Figure 3. Steel products capabilities by Steelmaking Process

Wire Rod

High grade ← | → Low Grade

- Bearing
- Valve Spring
- Tire Cord
- Alloy
- Suspension Spring
- Piano Wire
- Machine Structural
- Cold Heading
- Low Carbon
- Rebar

BF - BOF

EAF (SCRAP)

high HBI/DRI utilization — EAF (HBI/DRI and SCRAP)

Hot Rolled Coil

High grade ← | → Low Grade

- Draw & Iron Can
- Automotive (Exposed Parts)
- Deep Drawing Quality
- Line Pipe
- Automotive (Interior Parts)
- Drawing Quality
- Construction
- Welded Pipe

BF - BOF

EAF (SCRAP)

high HBI/DRI utilization — EAF (HBI/DRI and SCRAP)

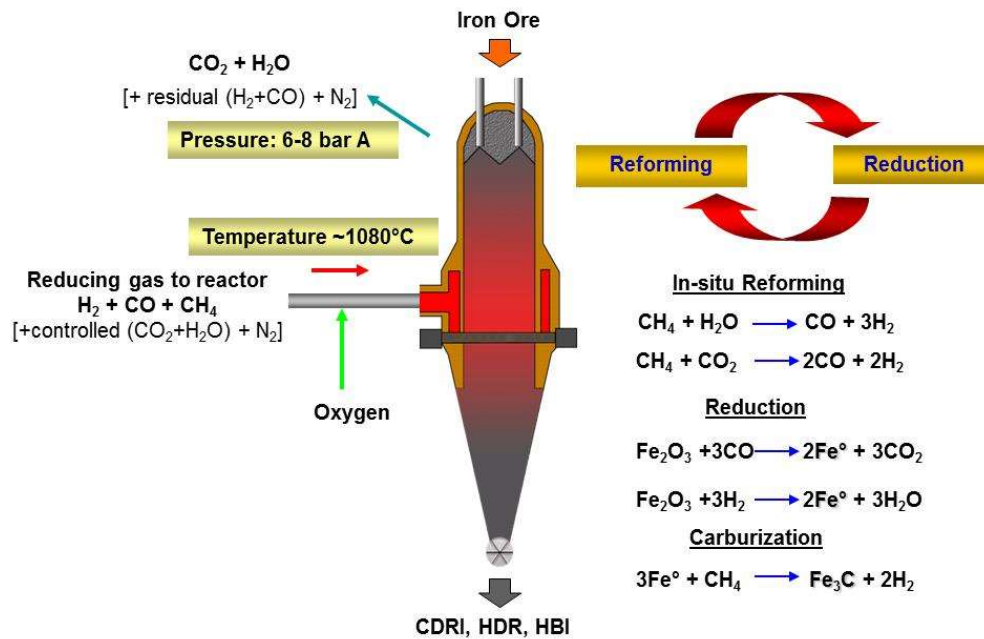## 3. Fundamentals of the ENERGIRON ZR Process

The ENERGIRON ZR Process scheme (Figure 4) is a major step in reducing the size and improving the efficiency of direct reduction plants. Reducing gases are generated by *in-situ* reforming within the reduction reactor, feeding natural gas as make-up to the reducing gas circuit and injecting oxygen at the inlet of the reactor [1].

The basic ZR scheme permits the direct use of natural gas. ENERGIRON plants can also use conventional steam-natural gas reforming equipment as an external source of reducing gases, which has long characterized the process. Other reducing agents such as hydrogen, syngas produced from coal gasification systems, pet coke and similar fossil fuels, and coke-oven gas, among others, are also potential sources of reducing gas, depending on the particular situation and availability. In any case, the same basic process scheme is used regardless of the reducing gas source.

The current configuration of this technology employs a continuous reactor (shaft furnace) based process, with both the product quality and process efficiency having been significantly optimized over the years. The ENERGIRON ZR technology is currently the most flexible option for producing DRI based on its uniquely simple process configuration and its wide flexibility for using different energy sources and available raw materials.

The Fe° formed in the process itself acts as the necessary, renewable and continuous "catalyst" for the reduction process. During start up, some H_2 and CO are generated by partial combustion (with oxygen injection) of process gas after process gas heater, starting reduction of iron ore.

Figure 4. ENERGIRON ZR Process: In-situ reforming

Iron Ore

$CO_2 + H_2O$
[+ residual $(H_2+CO) + N_2$]

Pressure: 6-8 bar A

Reforming   **Reduction**

Temperature ~1080°C

Reducing gas to reactor
$H_2 + CO + CH_4$
[+controlled $(CO_2+H_2O) + N_2$]

Oxygen

In-situ Reforming

$CH_4 + H_2O \longrightarrow CO + 3H_2$

$CH_4 + CO_2 \longrightarrow 2CO + 2H_2$

Reduction

$Fe_2O_3 + 3CO \longrightarrow 2Fe° + 3CO_2$

$Fe_2O_3 + 3H_2 \longrightarrow 2Fe° + 3H_2O$

Carburization

$3Fe° + CH_4 \longrightarrow Fe_3C + 2H_2$

CDRI, HDR, HBI

Operating conditions of the ZR process are characterized by high temperature (~1080°C) and high pressure (6-8 bar A at top gas). The elevated pressure allows a high productivity of about 10 t/h x m² and low reducing gas velocities of about 2 m/sec, as compared to lower operating pressure processes for which the gas velocities are >5 m/sec. The lower gas velocities reduce dust losses through top gas carry-over, thus lowering the overall iron ore consumption, which in turn lowers the overall operating costs. A distinct advantage of this process scheme without an integrated reformer is the wider flexibility for DRI carburization.

## 4. DRI Quality: High-Carbon DRI and the formation of Iron Carbide (Fe_3C)

As operational practice for ZR based DR plants, DRI can be produced with metallization of 94% - 96%.

$$\% \ Mtz \ (metallization) = Fe° \ (metallic \ iron \ in \ DRI) / Fe_{tot} \ (total \ iron \ in \ DRI)$$

DRI carbon levels can be obtained from ~ 1.5% up to 4.5%, regardless whether producing CDRI, HDRI or HBI, through the ENERGIRON ZR process, due to the prevailing conditions in the reactor's upper section:

- high methane (CH_4) concentration of >20%,
- H_2/CO ~ 4-5,
- the high temperature of the bed (>860°C),

which favors the diffusion of Carbon into the Iron matrix and the precipitation of iron carbide.

$$3Fe° + CH_4 \rightarrow Fe_3C + 2H_2$$
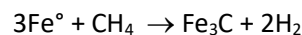
Cementite contains 6.69% carbon by weight, thus above that carbon content in the Fe-C phase system, the alloy is no longer steel or cast iron, as all of the available iron is contained in cementite. In this paper the term iron carbide is used to indicate cementite (Fe_3C), although cementite is not the only type of iron carbide.

Figure 5. Cementite Crystal Structure, Fe₃C, metastable state in Fe-C system. C atoms are placed at an interstitial site of Fe triangular prism. In the center, a structure containing 4Fe₃C, on the right a Fe₃C structure built from octahedral of Fe atoms around C atoms [2]
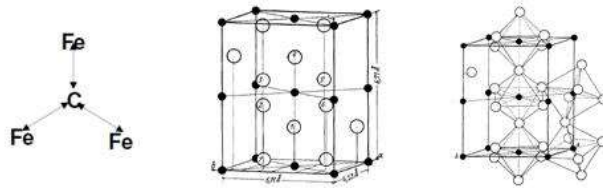
For several ENERGIRON DR plants based on the ZR scheme, 3.5% - 4.5% C in DRI is a typical medium value based on standard operational practice. However, higher values (over 5%C in DRI) are possible, up to saturation at about 5.7 % C in DRI (depending on the total Fe content in the iron ore). However, this is not recommended, as higher amounts of free carbon will be formed under such conditions.

In general, when the percentage of carbon in DRI increases, the amount of free carbon also increases. For any given total carbon content in DRI, the amount of free carbon will be much higher in DRI produced by a competing DR technology as compared to ENERGIRON DRI. Figure 6 presents the fraction of the total carbon present as iron carbide for ENERGIRON ZR process and the other DR technology [3].

Free carbon poses disadvantages such as less DRI stability and lower yield /energy efficiency in the EAF.

As can be seen from the graph below (Figure 6), in a DRI with 4 % (weight) total carbon content, 93% of the total carbon is present as Fe_3C. This corresponds to 3.72% of carbon weight as Fe_3C.

Because one atom of carbon will link three atoms of iron; 3.72 % of carbon as Fe_3C corresponds to 55.6% (weight). This means that the DRI produced by the ENERGIRON-ZR contains more than 50% of the total weight as Fe_3C.

On the other hand, for another DR technology, the maximum %C (as per actual plants results) are: max. of about 2.8%C for CDRI, max. 2.3%C for HCDRI (or simultaneous production of CDRI and HDRI) and typical figures of about 0.8-1.5%C for HBI. For CDRI production, NG can be injected through the cone, thus increasing the %C. For HDRI production, some NG is injected to the cone/middle section of the shaft. For HBI production, in order to discharge the HDRI at the maximum possible temperature, any NG injection is limited and thus the %C is low.

Figure 6. Fraction of the total carbon present as iron carbide: Comparative analysis for ENERGIRON ZR and Competing DR process
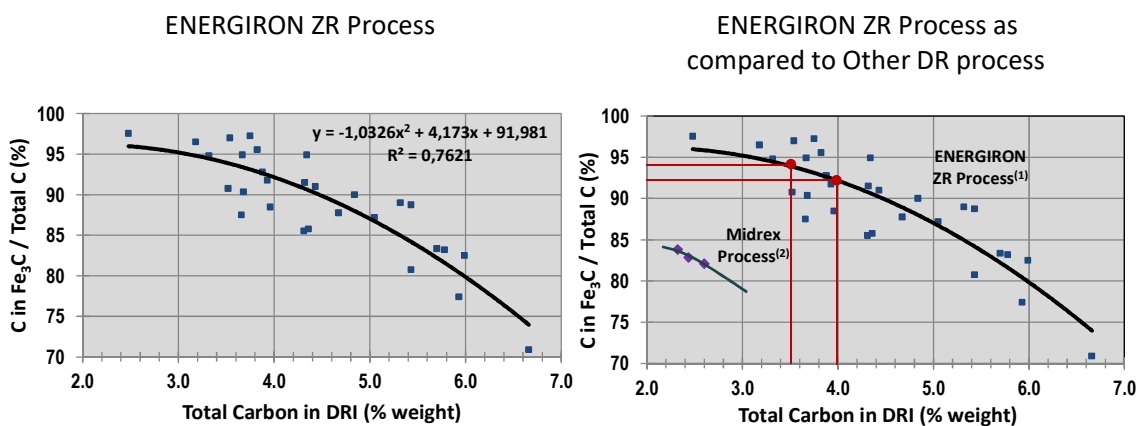
[1] *Industrial campaign for various Carbon levels in DRI at 4M ZR plant, Hylsamex in 1998-1999, Monterrey, Mexico.*
[2] *Lab tests from IAS (Instituto Argentino de Siderurgia) for Tenaris Siderca, Campana, Argentina, dated 11/23/01. Determinación del Carbono Cementítico y Carbono Libre, muestra 10/19/01.*

Typical DRI analysis for High-C DRI and conventional DRI are presented in Table 3 below.

Table 3: High-Carbon DRI and standard DRI analysis

High-C DRI Analysis – Nucor DRP:		"Conventional" DRI analysis:	
Metallization	96%	Metallization	94%
Carbon	4.3%	Carbon	2.2%
Fe°	87.3%	Fe°	89.2%
Fe Total	90.9%	Fe Total	92.9%
Fe_3C	58.5%	Fe_3C	29.6%
Gangue	3.8%	Gangue	3.9%

5. Characteristics of High-Carbon DRI

5.1. Stability and Safety

Extensive tests have been carried out to determine whether the combined carbon in DRI was a factor in improving product stability over that of conventional DRI, whether produced by the ZR-based plants or other process technologies. This has been proven through industrial operations and by specific internal and independent external laboratory tests. In general, the stability of DRI is related to the tendency to be re-oxidized, thus generating combustible gases which may cause firing/explosions. This behavior is normally predicted through laboratory tests by:

- *Oxygen Demand Reactivity Test* (ODR). This test corresponds to the determination of liters of oxygen consumed per ton of DRI per day @ 65°C.

- *Substances that in Contact with Water Emit Flammable Gases*. This test is conducted to determine the propensity of the sample to generate flammable gases when in contact with water.

In this regard, the High-C DRI, as per tests carried out by Chilworth Technology Ltd, UK on March, 2008, has been demonstrated to be a safe material in terms of:

- ODR: "negligible" l/ton/day, and
- Rate Generation of Flammable Gases: "0" l/hr/kg.

- *Aerated Powder Tests*. This test is conducted to determine information on the thermal stability of solids substances at elevated temperatures, to estimate the Onset Temperature or limiting temperature for thermal activity. The higher the result, the more stable the DRI.

- The Onset Temperature for High-C DRI showed an exotherm of 206°C to 212°C under ambient air and air saturated with water (at 25°C & 40°C), much higher than the typical figure of ~140°C for standard DRI.

Figure 7. Oxygen Demand Reactivity Test (ODR) and Substances that in contact with water emit flammable gases-gas generation in l/hr/kg

Danieli Oxygen Demand Reactivity (ODR) Test

Direct Reduced Iron

Oxygen Concentration (%) / Temperature (C) vs Time (hours)

— Oxygen Concentration   — Sample Temperature
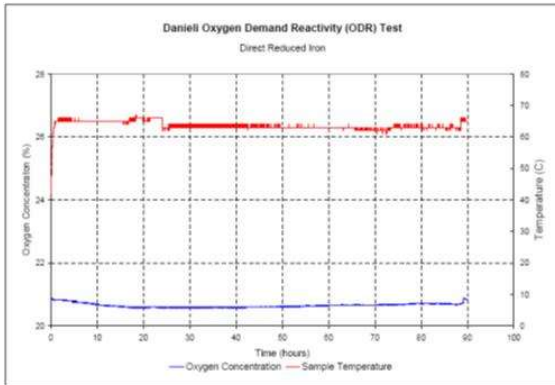
Test Number	Water type	Temperature (°C)	Maximum rate of gas generation (l/hr/kg)
1	distilled	ambient	0
2	distilled	ambient	0
3	distilled	ambient	0
4	sea	ambient	0
5	sea	ambient	0
6	sea	ambient	0
7	distilled	40	0
8	distilled	40	0
9	distilled	40	0
10	sea	40	0
11	sea	40	0
12	sea	40	0
13	distilled	80	0
14	distilled	80	0
15	distilled	80	0
16	sea	80	0
17	sea	80	0
18	sea	80	0

Similar tests on High-C DRI were carried out by the Korean Institute of Fire Industry & Technology on March 2012, showing and confirming the tests performed by Chilworth Technology Ltd, UK.

5.2. Energy in the High-Carbon DRI

In general, the higher the metallization of DRI, the higher the energy saving in the EAF. As a rough figure, 1% metallization above 90% is equivalent to ~12 kWh/tLS.

On the other hand, iron carbide is a metastable phase and at certain temperatures will decompose to metallic iron (austenite or ferrite) and solid carbon (graphite). That process is called "cementite decomposition" and is a very well-known event that also helps to explain why certain DRI products present a wide amount of carbon in the form of graphite, while certain other DRI products present more benefits due to a wider amount of carbon bonded with iron in Fe_3C form.

When the DRI pellet containing Fe_3C enters the metallic bath it will start to melt, absorbing the energy of the liquid around it. At the typical liquid steel bath temperature, after that the DRI pellet has gone through the slag, heating up and after being submerged in the steel, the cementite will cross its solidification temperature of 1227°C and start to dissociate. In the EAF bath, the ΔG (Gibbs free energy) for Fe_3C dissociation is negative, so that reaction can proceed spontaneously without external inputs and will release heat.

1) Fe_3C → $3Fe + C$ $\Delta G_{1400°C} = -522.7$ kJ/mol Fe
2) $2C + O_2$ → $2CO$ $\Delta G_{1400°C} \approx -530.0$ kJ/mol O_2

Once the Fe_3C has dissociated, the iron units will be part of the molten bath, while the carbon atoms will start looking for their best option to combine. In the case of the CO reaction, we have the situation in which one mole of oxygen reacts with carbon to produce two moles of CO. The volume of gas is increasing, the entropy is increasing and therefore, with temperature increase CO becomes increasingly stable. CO_2 stability is lower than CO (lower negative value of ΔG) at bath temperatures, so the reaction that is going to take place between carbon and oxygen is the one to form carbon monoxide.

Different studies have been carried out in the melt shop at Ternium Hysla in Monterrey (feeding the EAF with a charge of 100% hot DRI with about 94% metallization and 4% carbon), and also in the two melt shops of Emirates Steel Industries in Abu Dhabi (feeding the EAF with 100% hot, high carbon DRI charge). The data collected in

those plants is in fact showing that the combination of the reactions 1) and 2) above, results in a net savings of ~37 kWh/tDRI per each 1% carbon in the DRI. Just for Fe_3C dissociation alone, the heat release is 8 kWh/tDRI per each 1% carbon [4].

In general, total chemical energy release from High-C DRI is 36 - 40 kWh/tDRI per each 1% carbon in the DRI, depending on the post combustion factor.

6. Hot DRI production and the HYTEMP® System

When a DR plant is located inside an integrated steel plant, the ideal condition is not to cool down the DRI but to feed it hot to the EAF. Sensible heat of HDRI at 600°C (with respect to 25°C) is 362.625 MJ/t DRI. Depending on the particular characteristics of the EAF, operational practices and DRI composition, this represents saving of 20 -25 kWh/tLS per each 100°C of DRI temperature.

There are different ways for feeding hot DRI to EAF, the most common being:

1. metallic conveying systems
2. gravity discharge
3. pneumatic transport

1. Metallic conveying systems, such Aumund conveyors, are used in some DR plants (not ENERGIRON), with ~6 years operation and with ~60% yearly availability initially (now it is claimed to be 80-100%). Some characteristics of this type of systems are:

   - Moving parts with intrinsic operative/maintenance provisions.
   - Intensive maintenance.
   - Transfer points limitation.
   - Rigid configuration.
   - Distance up to 250m.
   - max. Lift: 60°. Limitations for existing facilities in both, DR and meltshop.
   - Required inertization due to the long distance and open spaces, if "inert gas" which contains CO_2 is used, CO generation will occur which will lead to safety hazard. N_2 is required.
   - Dust collection to prevent Hot DRI dust from flying around.

2. HDRI charging by gravity is limited by:

   - Configuration and layout of the meltshop.
   - Space availability for installation of the DR reactor tower.
   - Capacity of the facility, which dictates the size and height of the tower.

3. The HYTEMP® system, developed by Tenova HYL since 1994, takes full advantage of the continuous feeding of HDRI to an EAF, maximizing the EAF productivity and minimizing the power and electrodes consumption. The HYTEMP® system is based on the concept of pneumatic conveying of bulk materials. For pneumatic transport of bulk materials, there are 2 basic possibilities:

   - Transport by using kinetic energy to the solids, which implies high carrier gas velocities. This corresponds to a dilute phase mode, or
   - Transport by using potential energy to the solids, which implies lower gas velocities by higher ΔP. This corresponds to dense phase mode.

For the HYTEMP® system, the design was made in order to optimize a safe DRI transport while minimizing fines generation during transport and power consumption, as indicated in Figure 8 below.

*Figure 8. Pneumatic transport of HDRI; conceptual phase diagram*
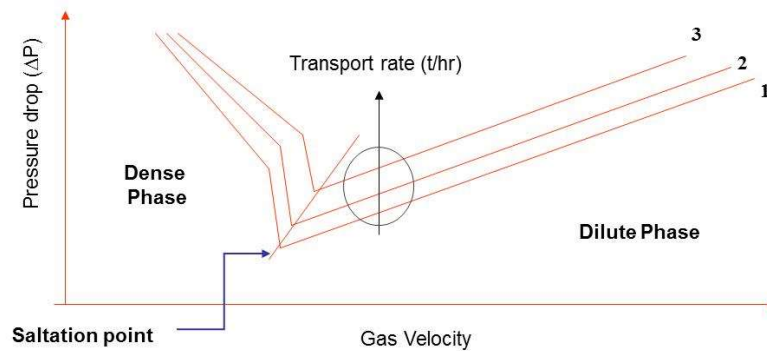
The DR plant is a continuous process while the EAF operation is batch; nevertheless, the matching of the two systems is possible when they are connected via a HYTEMP® system. To achieve this matching, the DR plant is provided with an external cooler to produce cold DRI whenever the EAF is out of operation. This can be stockpiled and then used in the meltshop whenever the DR plant is out of operation. The ENERGIRON DR plant with this configuration can simultaneously produce any proportion of CDRI and HDRI. The EAF charging bins are properly sized with adequate capacity to be used as a buffer to match both units. The configuration of this system is presented in Figure 9.

As compared to other HDRI transport systems, the HYTEMP® system is characterized by the following main features:

- It is a fully automated and integrated system for transportinghot DRI from the DR plant to the melt-shop and subsequent continuous feeding to the EAF.
- Totally enclosed system with minimum losses and the lowest environmental impact
- In principle, any non-oxidizing gas can be utilized for transport; normally N_2.
- The system complies with all safety regulations.
- Requires low maintenance efforts, therefore very low maintenance cost

*Figure 9. HYTEMP® system; left scheme configuration, right, ESI Abu Dhabi ENERGIRON DR plant*
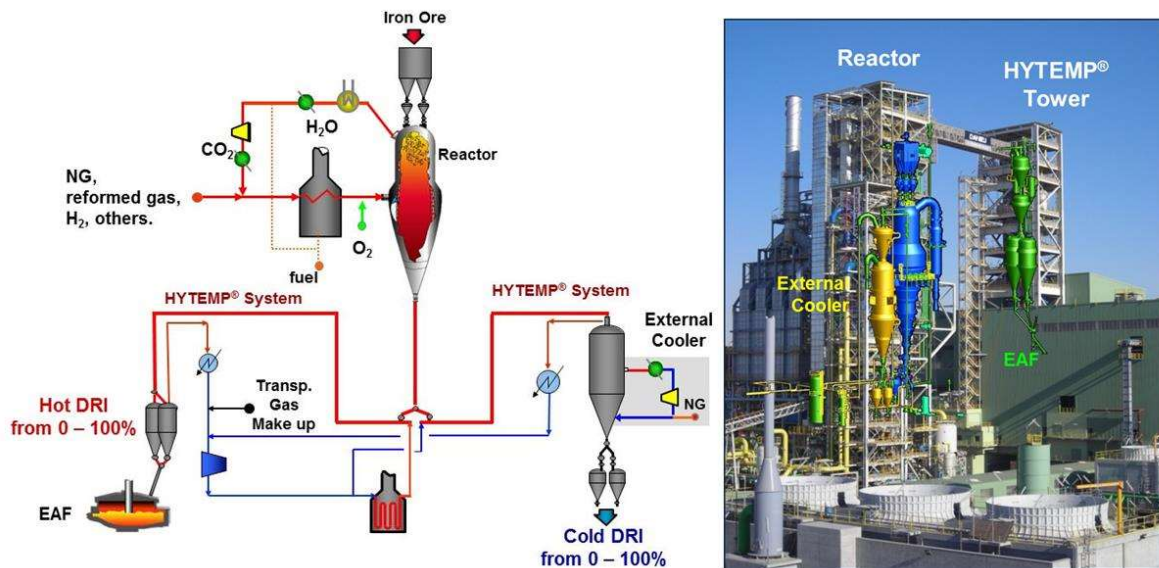
- There are no losses on the DRI quality (%Mtz and %C) during transport and feeding to the EAF.
- Insulated system with very low heat losses.
- It has flexible configuration to match the space available in the melt-shop with the most adequate arrangement of bins.
- There is no interference with the existing material handling, maintenance, or other activities, neither for the DR nor for the EAF because the connection between the two units is located at elevated position.
- System with no wearing parts, practically maintenance free. The only wear and tear component is the inflatable seals of the VS-2 valves.
- The same system can be designed to feed one or more EAF's in parallel from the same DR reactor with any split and at a controlled rate.
- The system power consumption is very low; 3 to 6 kWh/t DRI, depending on the transport rate.
- The system consumes only 5 to 8 Nm^3/ton of N$_2$ for the depressurization of the DRI at EAF feeding system.
- The system can easily be implemented even if the distance between the DR reactor and the EAF is relatively long (up to ~500 m).
- Its operation is highly reliable, with no impact on plant availability recorded by Ternium, and Emirates Steel.

This system has been in operation at Ternium steelmaking facilities since 1998, for ~90% hot DRI charge to EAF, with 100% availability since initial operation. No single pipe has been changed since then, reflecting the low maintenance of this system. Currently, there are four HYTEMP® systems in operation: Ternium Mexico, ESI#1 and ESI#2 in Abu Dhabi and Suez Steel Company in Egypt, all transporting HDRI with 100% availability. To date (2017), more than 30 million tonnes HDRI have been transported with this system.

DRI products and main applications are presented in Figure 10.

Figure 10. High-Carbon DRI products end-users
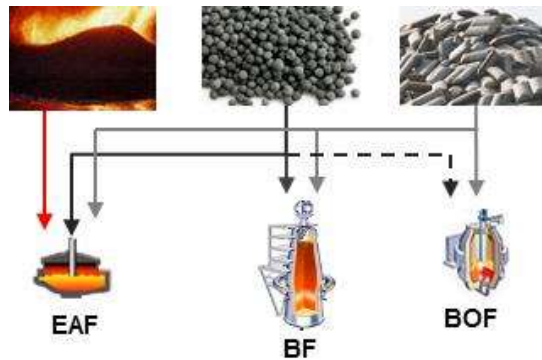
7. High-Carbon DRI in EAF

In general, melting of DRI in an EAF theoretically demands more electrical power because of the DRI gangue content, which also needs to be melted. The theoretical calculation indicates that for cold conventional low-Carbon DRI, the power consumption should be between 160 to 220 kWh/tls higher than for melting 100% high density scrap, which in the range of 360 – 400 kWh/tLS.

However, the difference in power consumption becomes very similar when comparing melting of 100% scrap vs 100% High-C HDRI in the EAF; power consumption is 380-410 kWh/tLS.

All the above is further improved when the DRI to be melted:

- contains High Carbon (more than 3%), and
- is further optimized if the DRI is fed at high temperature to the EAF.

Figure 11. High-Carbon HDRI feeding the EAF at Ternium Monterrey


The effect of temperature and %C of High-C DRI, as compared to conventional DRI in terms of power consumption, ~60 kWh/tLS and ~120 kWh/tLS less for 100% High-C CDRI and HDRI respectively, and power-on-time, is presented in Figure 12. The higher benefit of High-C HDRI becomes evident.

In general, the High-C HDRI provides very important benefits to the EAF:

- It contains additional energy as compared to the standard DRI, reducing the electrical power consumption and increasing the EAF productivity.

- Electric power savings in the EAF are about 37 kWh/tLS per each 1% of carbon in the DRI.
- The Oxygen injection flow is calculated to match the Carbon input from the DRI and it is controlled according to the DRI feeding rate. Since Carbon and Oxygen are continuously added throughout the complete heat, a foaming slag is permanently present in the EAF.
- Due to the high CO generation, it is very easy to create and maintain throughout the melting process a foamy slag that protects the furnace wall from the radiation of the arc.
- The carbon in the DRI is pure, does not contain ashes, sulfur, volatile matter, etc. which are detrimental to the steel quality and/or to the melting process.
- The DRI chemical analysis is totally known and the behavior can be 100% predicted.
- The carbon in the DRI minimizes or eliminates the use of external carbon. The DRI carbon is essentially "injected" continuously at the same rate as the iron.
- High percentages of DRI can be fed continuously to the EAF without opening the roof.
- The feeding rate is controlled to match the power input in such a way that the temperature of the melt is kept fairly constant. The feeding rate (kg/min-MW) depends on the DRI quality and temperature.
- The DRI can be fed up to 100% in the EAF since the melting of the pellet is faster because of the smaller particle size.
- Additionally, the EAF is electrically more stable, (less flicker and higher power factor).

Figure 12. Effect of High-Carbon DRI and Temperature in EAF
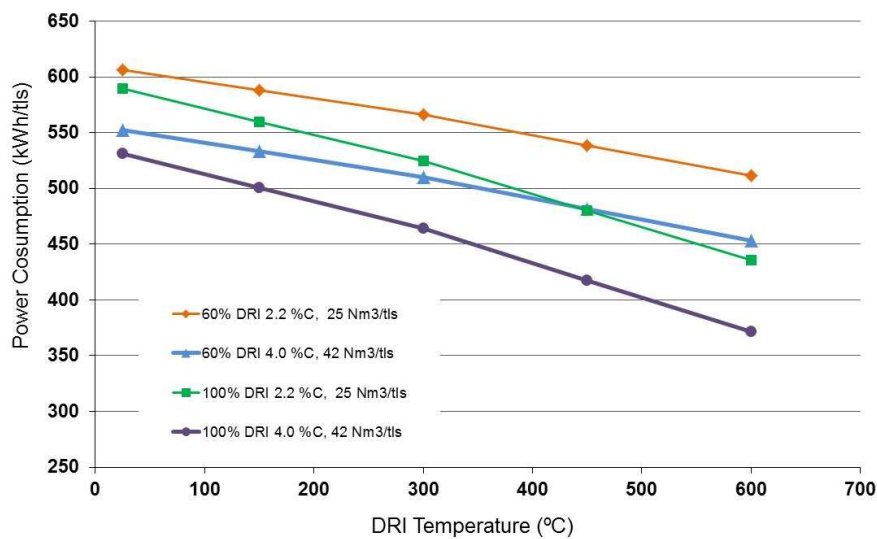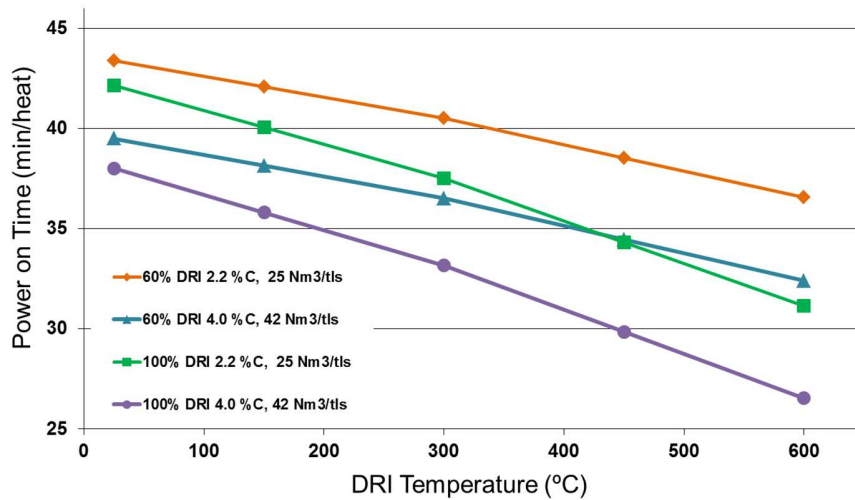
Ultimately, what really matters is the actual EAF operation and experience when using High-C DRI, which has been publicly mentioned by a number of meltshop operators;

"Much of the DRI currently in use at the mill comes from Nucor's plant in the US state of Louisiana, which has proven easier to handle than DRI from the company's unit in Trinidad & Tobago", according to Tirabassi. In the furnace, 2.5% carbon DRI is more challenging to work with than high carbon DRI, as the latter boosts a furnace's efficiency more readily", he said.

Nucor Steel Louisiana produces premium DRI with metallisation rates of 96% and carbon content of 3.64%. *"As an operator, there's a lot of difference [between Louisiana sourced DRI and material from Trinidad],"* Tirabassi said. *"They act differently; It's a totally different balance."* [5].

8. High-Carbon DRI/HBI in BF

DRI/HBI can be used in the BF as pre-reduced material, partially replacing the traditional ferrous feed consisting of lump ore, sinter and oxide pellets.

By feeding DRI/HBI into the BF, there are two possibilities, which will improve the BF operation in terms of productivity and/or coke input requirements:

1. Liquid steel production rate is kept while environmental impact is reduced due to a decrease of specific coal (coke/PCI) consumption and consequently a reduction in CO_2 emissions.
2. Increase the BF productivity, decreasing not only the specific consumption figure, but also achieving savings in production costs.

The use of DRI and mainly HBI, as metallic charge to BF has been well documented as per tests and operating practices reports in several integrated steelworks. According to available data, DRI/HBI charge to BF allows a significant reduction of fossil fuels specific consumption. As per reported values indicated in Figure 13 (left graph), there is a correlation between the decrease of coke consumption and increase of productivity as a function of the metallized burden in the feed charge. In general, for each 10% of burden metallization in the mix charge, the coke rate can be decreased by 6% to 7% while the productivity can be increased by 7% to 8%. All these reported results are based on the use of conventional DRI/HBI, which implies carbon levels not higher than 2.0%C.

By using instead High-C CDRI/HBI (~4.0%C), a further decrease of the PCI/coke consumption and increase of the BF productivity can be expected. As mentioned in point 3 above, more than 90% of the carbon in the High-C DRI is in the form of Fe_3C.

In this respect, the following additional benefits are expected when using High-C CDRI/HBI to the BF:

- The secondary reduction of the remaining wustite (FeO) in DRI with the carbon. This reduction reaction generates CO gas which can also reduce the iron ore around the DRI, improving furnace efficiency and decreasing PCI/coke requirements. This effect is limited with the traditional DRI/HBI with lower carbon content. Refer to Figure 13 (right graph) for the effect of the High-C DRI in the BF.
- The additional energy provided by the excess of carbon in the DRI.

According to this analysis, the PCI/coke rate can be decreased down to 8% to 9% while the productivity can be increased up to 9% to 10% for each 10% of metallized burden in the feed charge, when using High-C DRI/HBI [6]. In this regard, there are other similar analyses related to the use of High-C DRI/HBI in the BF [7], which indicates a higher impact of this material as metallized burden in connection to further PCI/coke reduction and productivity increase due to, not only the secondary reduction of FeO but also to a more optimized BF operation.

In an integrated steel works, the excess of coke oven gases (COG), converter gases (BOFG) and blast furnace top gases (BFG) are sent to a power plant to generate electric energy for the in-plant users and there is always an excess which is exported. This contributes to CO_2 emissions of ~1800 kg CO_2/tLS, assuming there is no CO_2 credit for power export or ~1600 kg CO_2/tLS when there is such credit in a location of 0.5 kg CO_2/kWh. The impact on CO_2 emissions when using High-C DRI/HBI, as compared to standard DRI/HBI becomes evident, as indicated in Table 4 [6].

Figure 13. Coke rate decrease and production increase in function of burden metallization in BF.
Left, reported results by existing integrated steelworks. Right, estimated impact by charging High-C DRI/HBI to BF
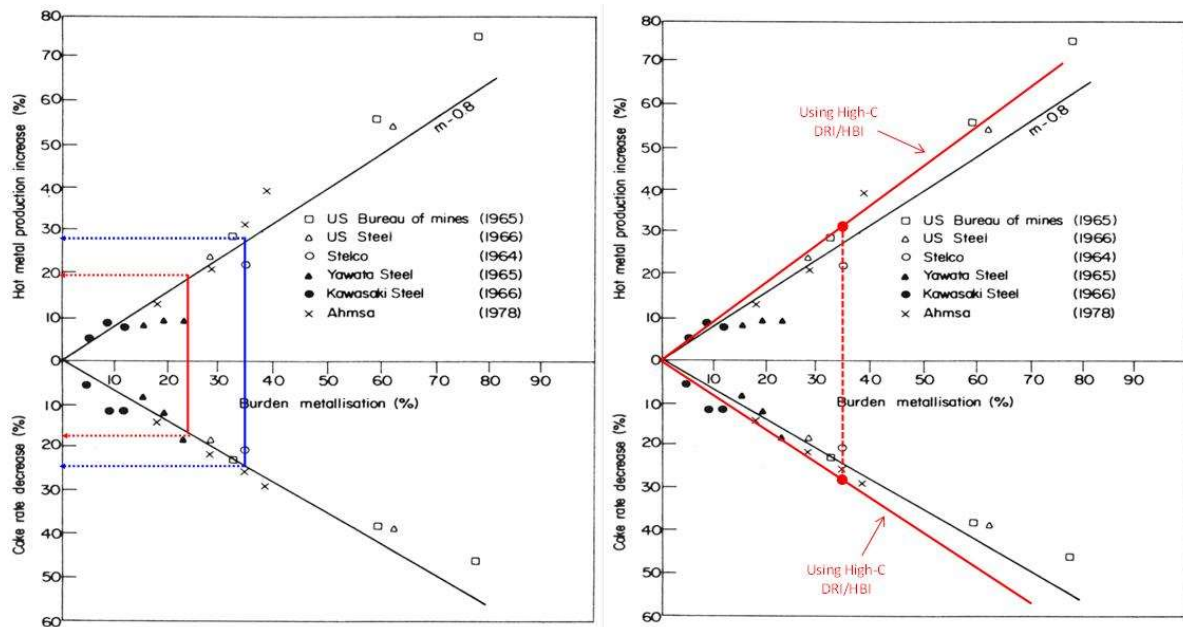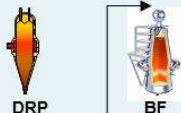
Table 4. Effect of High-C DRI vs. Standard DRI to BF in terms of CO₂ emissions and for different power carbon-footprint considerations.

DRI/HBI feeding to BF Approach [35% burden Mtz charge; ~400 kg coke-PCI/tHM]	
DRP → BF	DRP → BF
• DRI from abroad: CO_2-neutral (except %C in DRI/HBI)	• DRI in the BF installation: CO_2 from NG, iron ore included
• Power input: CO_2-neutral	• Power: location of 0.5 kg CO_2/kWh
• Export power from BF-BOF: no credit	• Export power from BF-BOF: CO_2 credited
• BF-BOF emissions: 1800 kg CO_2/tLS	• BF-BOF emissions: 1600 kg CO_2/tLS

CO_2 Emissions [as % with respect to BF-BOF installation: 100% and based on kg CO_2/tLS]			
Standard DRI/HBI (Other DR technology) selective CO_2 removal: Not available			
80%		89%	
High-C DRI/HBI (ENERGIRON ZR) with and w/o selective CO_2 off-taking/commercialization			
w/o	with	w/o	with
74%	74%	87%	83%

9. High-Carbon Briquette

HBI is characterized for inherent advantages for handling, storage and overseas transport. On the other hand, as indicated in point 6 above, the benefits of using High-C DRI in EAF shops are very well known, as it provides additional chemical energy resulting in higher productivity and lower power consumption, reducing the EAF OPEX. By combining these two properties, High-C DRI with carbon content above 3.0% can be produced through the ZR process and then molded into High-C Briquettes, a unique and novel merchant product, fitting specific market needs.

Tenova HYL has conducted several HBI test programs that goes back to late 80's -before the first HYL HBI Plant was built- until recent years. Some of these tests have been carried out with the support of Köppern GmbH & Co. KG in its facilities at Hattingen, Germany. The most recent test works consisted of testing High-C DRI produced in the Emirates Steel #3, ZR Micro-Module DR plant located in Abu Dhabi, UAE and, more recently, using the High-C DRI from 3M ZR DR plant at Ternium Monterrey [8].

HBI, as per IMO directions for overseas export [scheduled as DRI(A)], must comply with a density of 5.0 kg/m³. However, the higher the %C the lower the density, simply because of density difference between Fe and C. As per the above mentioned tests, High-C HBI presents a density of 4.8 - 5.0 g/cm³, depending on:

- Iron ore origin and characteristics (Fe_{tot}, gangue)
- DRI particle size

- DRI temperature
- HBI cooling method
- % carbon in the DRI

For inland transport and domestic distribution, the density is not a factor; what is more important is the integrity of the briquette during handling, to avoid fines generation that have higher tendency to re-oxidize. Therefore the main parameters defining the quality of HBI are: i) the compression strength (in MPa), which is a more indicative parameter in terms of handling and exposed surface, and ii) the abrasion resistance [R30(1000), as %], which indicates the integrity of the briquette in terms of fines generation, and which is about the same as the standard low-C HBI.

For the above mentioned tests, the High-C DRI chemical composition is shown in below Table 5.

Table 5. High-C DRI analysis

Component DRI	% weight
Fe Tot	90.55%
Fe met	85.39%
Gangue	4.29%
Metallization	94.30%
Carbon	3.68%

The main variables considered for the tests were i) DRI particle size (entire, crushed pellets), ii) briquetting temperature and iii) HBI cooling method. Sample coding was classified as indicated in Table 6. Table 7 summarizes the test results by each tested sample.

Table 6. High-C HBI tests: Sample coding as per considered variables

Test	DRI particle size	Temperature (*)	Cooling Method
T.01	Entire	720 °C / 640°C	Type a = ambient air
T.02	Entire	683 °C / 538°C	Type b = water spraying
T.03	Crushed	732 °C / 628°C	Type c = water quenching
T.04	Crushed	758 °C / 678°C	

(*) Note: Temp. before feeding / Temp. on briquette after pressing

Table 7. High-C HBI tests results

Test	Density (g/cm³)	Shatter Strength (%)	Compression Strength (N)	Tumbling Strength (%)
T.01	5.05	91-95	> 9,000	84-85
T.02	4.96	81-88	> 9,000	65-76
T.03	4.93	98	> 9,000	91
T.04	5.08	97-98	> 9,000	90-94

As can be observed from Table 7, the density in all samples is about 5.0 g/cm³, which is the requirement in accordance with current IMO regulations for HBI transporting. The shatter test shows values for grain sizes > 20mm is a more than 90% while the tumbling tests shows values >85%. The most impressive and important result was the compression strength which in all cases was >9,000 N (machine limit) and there were no broken briquettes. The test T.02 resulted in lower values since material temperature was lower as can be noted in Table

6. In general, all strength related testing results have demonstrated that produced High-C Briquettes have acceptable strength and density values which are totally comparable to the traditional HBI product currently in the market, but with the significant difference that the High-C Briquettes will provide additional chemical energy when being melted in the EAF.

10. References

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