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COREX® - AN ANSWER FOR HOT METAL PRODUCTION IN A CHANGING ENVIRONMENT*

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Abstract

The COREX® process is beside the FINEX® technology the only industrially realized alternative to the blast furnace route for the production of hot metal. Changes in the raw material sector in respect of decrease in quality, strictly enforced environmental laws and positive operation results of COREX® reference plants make it worth to carefully re-evaluate the COREX® technology in comparison with the traditional blast furnace technology. Integrated Plant concepts based on COREX® offer solutions for future challenges of the iron- and steelmaking industry, which include: economical hot metal production; efficient and highly economic export gas utilization (power generation, DRI production, syngas production for chemical products); lower raw material cost, higher raw material availability; environmental friendly high grade steel production. The economic evaluation of different COREX® gas based plant concepts in comparison with the traditional blast furnace route shows that the COREX® technology is highly competitive in the challenging iron and steel producing environment.

Keywords: COREX®; Economics; Status of plants.

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The COREX® Process

COREX® is a commercially proven smelting reduction process that allows for cost-efficient and environmental friendly production of hot metal directly from iron ore and non-coking coal. The process was developed to industrial maturity by PRIMETALS and is beside the FINEX® Process the only alternative to the blast furnace route consisting of sinter plant, coke oven and blast furnace for the production of hot metal.

1. STATUS OF OPERATING COREX® PLANTS

POSCO Pohang Works (Korea) - 1 x COREX® C-2000 Module

Figure 1: COREX® POSCO C-2000, later converted to the FINEX® F-0.6M

Start-up of the first COREX® C-2000 plant took place in 1995. The COREX® export gas was utilized for power generation. In parallel with the signature for the COREX® plant contract in December 1992, POSCO and PRIMETALS signed a co-operation agreement for the joint development of the FINEX® process. Following initial laboratory, bench scale and pilot-plant tests. In 2002 this COREX® plant was converted into the FINEX® F-0.6M Demonstration Plant with a nominal capacity of 2000 t/d and which commenced operation in 2003.

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ArcelorMittal Steel South Africa / Saldanha Works (South Africa): 1 x COREX® C-2000 and 1 combined COREX® gas based MIDREX™ DR plant

Figure 2: COREX® AM South Africa

The COREX® C-2000 plant and the Midrex DR plant started-up in 1999. The export gas from the COREX® plant is used in the **COREX® gas based MIDREX® DR** plant. Highlights for these plants are:

- The COREX® plant operation is based on the high ratio of approx. 85% local lump ore charging.
- Typical annual production for the COREX®/ MIDREX™ DR plant combination is 700,000 t/a HM and 700,000 t/a DRI.
- Compared to other ArcelorMittal plants, the hot metal cost in this steel works is one of the lowest production cost within ArcelorMittal group.

Jindal South West Steel (India)
2 x COREX® C-2000 and 1 combined COREX® gas based MIDREX™ DR plant

Figure 3: COREX® JSW Module 01

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Start-up of COREX® C-2000 plant Module 01 and 02 took place in 1999 and in 2001 respectively. The COREX® export gas was utilized for pellet production, for internal use and for power generation in a dual fired conventional steam power plant. Highlights for these plants are:

- In 2014 a COREX® gas based 1.2 million t/a MIDREX™ DR plant was successfully added to produce Hot DRI. COREX® export gas from both modules is partly used for Hot DRI production which is subsequently transferred to a new adjacent EAF steel plant via a hot transport system. The remaining export gas is still used for internal steel works use, the pelletizing plant and the power plant for co-firing.

Figure 4: The AGD in place at COREX® Baosteel Module 02

During the relining in 2012 and 2013 an Arial Gas Distribution System was introduced in the reduction shaft of each COREX® module. As a result, due to the changed process parameter (more even gas distribution, less burden weight on the DRI screws, more even flow of the material through the reduction shaft, etc.) an improvement of the process itself could be achieved:

- o Improved gas distribution
- o Lower delta p over the reduction shaft
- o And very important: The "shaft lifetime" meaning the time from one shaft cleaning to the next shaft cleaning that occurred at JSW on a regular basis has now been elongated to more than one year. This is also confirmed by the operation of the BAOSTEEL COREX® plant module 02 where no shaft cleaning was necessary during its operation time of 1.5 years.

<u>Shanghai Baosteel Group (China) - 2 x COREX® C-3000 Modules</u>

The first industrial COREX® C-3000 with an annual capacity of 1.5 million t of hot metal was built at the new steel works of Baosteel in Luojing at the outskirts of Shanghai. The plant started-up in November, 2007. The contract for a second COREX® C-3000 plant has been signed in December 2007 and was started-up successfully in March 2011.
In Module 02 many improvements compared to Module 01 were installed that subsequently resulted in a successful performance guarantees test shortly after start-up where all agreed performance parameters have been achieved and even exceeded.

Figure 5: COREX® Baosteel Module 01

Due to declining prices for heavy plate and as part of a strategic realignment of production in the Shanghai area, Baosteel has decided to cease steel production in the Luojing Works and dismantle the individual steelmaking installations, including the two COREX® plants. It rebuilt the dismantled installations in various Chinese steel works. The COREX® Module 01 has been transferred to Bayi Steel in the Xinjiang Province and is supposed to start operations in Q3 2016.
In contrast to the conventional blast furnace route, the COREX® plant at Bayi Steel will allow local coal to be used, which are significantly cheaper in Xinjiang area. Secondly, it offers an additional advantage in that the COREX® export gas can be used as a fuel gas in the downstream facilities to generate electricity or for the production of direct-reduced iron in a region that has almost no resources of natural gas.

Essar Hazira Ltd. (India) - 2 x COREX® C-2000 Modules

The first plant has been started-up successfully in August 2011. Start-up of the second plant took place in December 2011. The COREX® Export gas is mainly utilized at the existing MIDREX™ DR Modules to minimize natural gas consumption and for internal heating purposes. Highlights for these plants are:

- Most of improvements available at the time of start-up have been incorporated leading to a smooth start-up and continuous operation of both COREX® plants.

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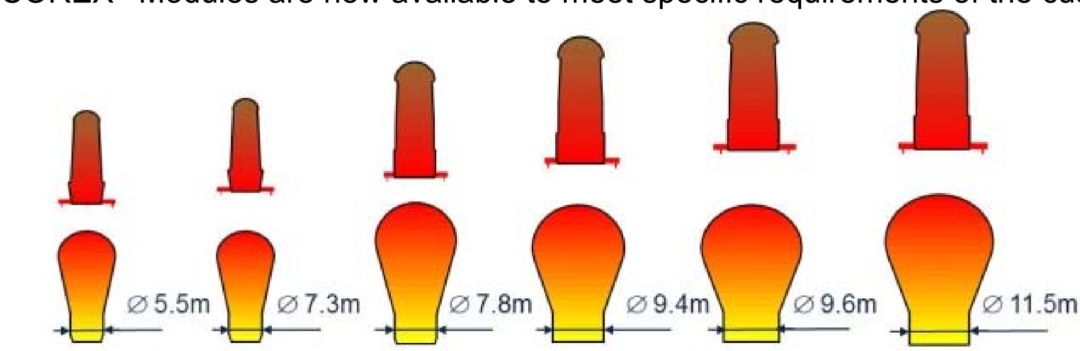
Figure 6: COREX® Essar Module 01

2. COREX® MODULES

Compared to the few modules available in the past, several different sizes of COREX® Modules are now available to meet specific requirements of the customers:



C-1000 C-0.5M	C-2000 C-0.8M	C-1.0M	C-1.3M	C-1.5M	C-2.0M
40 - 60 t/h	80 - 100 t/h	100 - 125 t/h	125 - 160 t/h	160 - 180 t/h	210 - 240 t/h
	600,000 - 800,000 t/a	800,000 - 1,000,000 t/a	1,000,000 - 1,300,000 t/a	1,300,000 - 1,500,000 t/a	1,700,000 - 2,000,000 t/a

Figure 7: Up-scaling COREX®

3. COAL BRIQUETTING

Enhancing raw material spectrum, utilization of coal undersize and utilize full potential for waste recycling and alternative iron and fuel carriers in the COREX® process had been the incentive for development of respective suitable briquetting methods.

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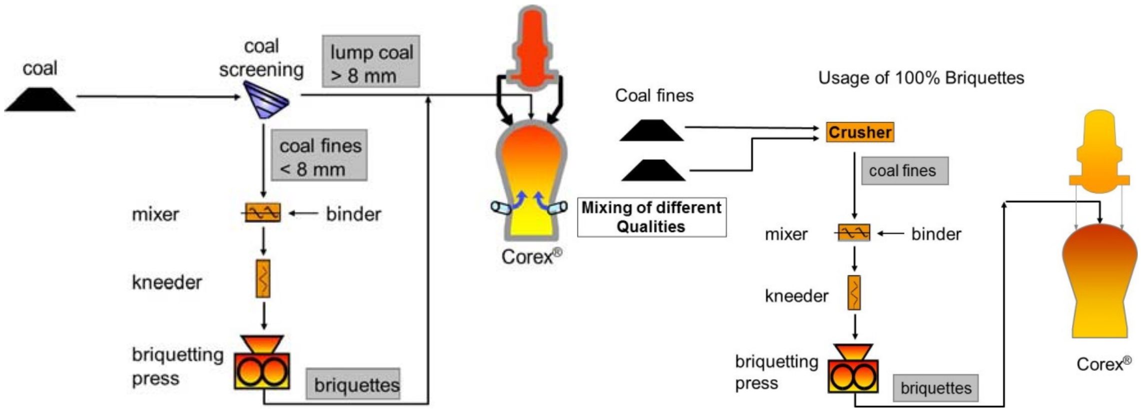

Figure 8: Undersize briquetting (up) - Usage of 100% coal fines (down)

The key element for a successful coal briquetting is less a matter of equipment than the process know-how and expertise in the field of chemical and physical briquette properties. The benefits of coal briquetting are:

- Usage of all the coal in fine and in lump condition as delivered to plant
- Usage of lower quality coal - using out of range coals
- Stabilization of char bed and therefore optimum plant performance with lowest coke rates

	Indices	V.M (%)	Ash (%)	FSI	BF		COREX®
Coal Briq.	Thermal Coal	30~38	< 17	0~2			15%
	Semi-Soft Coking Coal	28~34	< 10	1~6	40%	PCI	Coal Briq. 75%
	Hard Coking Coal	20~25	< 10	6~9	Coke		10%
PCI	Semi-Anthracite	10~15	< 15	0~2	60%		

Figure 9: Quality of coals that can be used in COREX® compared to the blast furnace route

For the economic assessment of the operation costs the following two alternative plant configurations have been selected:

- COREX® plant with undersize coal briquetting
- Pelletizing plant (supplying also the pellets for the DR plant in Alternative 2)
- Air separation plant
- Power plant (Alternative 1) / direct reduction plant (Alternative 2)

Main products of these plant configurations are hot metal and electrical energy (for Alternative 1) and (hot) DRI (for Alternative 2) respectively.

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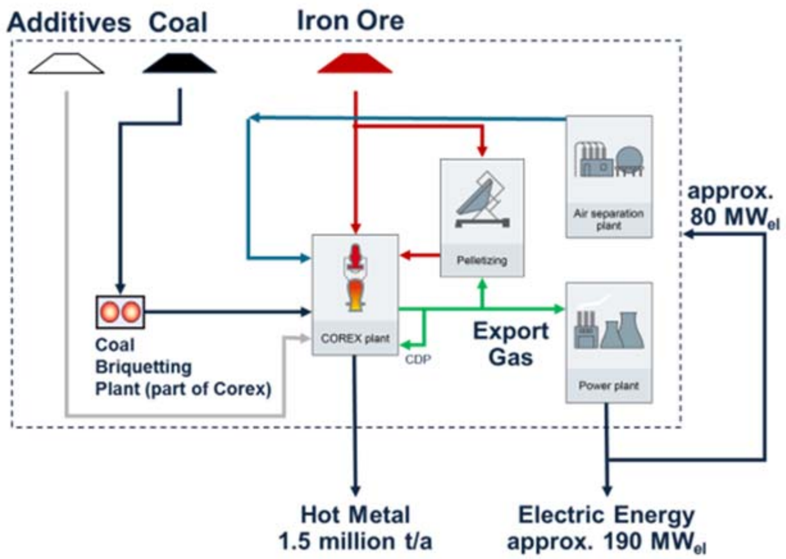

Figure 10: Alternative 1: COREX® based hot metal production with downstream export gas utilization in a combined cycle power plant

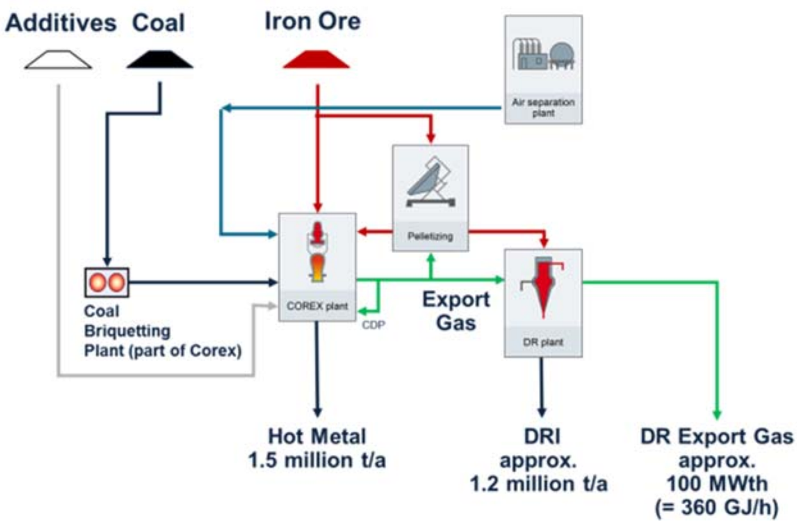

Figure 11: Alternative 2: COREX® based hot metal production with downstream export gas utilization in a MIDREXTM DR plant

The advantages of the combinations are:

COREX® plant

- Lower investment- and production-cost to a comparable to the blast furnace route (the blast furnace route includes blast furnace, sinter plant, coke oven plant, respective oxygen plant, respective storage areas for raw material, sinter, coke, infrastructural items, export gas utilization)
- Flexibility in operation and use of cheep raw materials
- Environmental friendly production of hot metal to be used in an EAF or BOF
- Major equipment improvements included e.g. AGD and a coal briquetting system allowing for highest economical hot metal production
- Valuable export gas for use in electric power generation or DR plant

Pellet plant

To fully utilize the advantages of the COREX® plant and to achieve low hot metal cost, it is recommended to simultaneously install a pelletizing plant that allows for

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utilizing low cost fine iron ores, even concentrates, from the market and wastes from the existing steel plant. The pellet production is based on the use of "low cost" COREX® export gas (valued in the calculation to 0 USD/GJ) to produce pellets for the COREX® plant (Alternative 1 and 2) and the DR plant (Alternative 2). The main advantages of the captive pelletizing plant are:

- Conversion of low-cost iron ore fines into pellets suitable for COREX® and the DR plant, avoiding the pellet premium due to production of pellets in areas with high energy cost (e.g. in India, Brazil or Australia)
- Utilization/recycling of steel works wastes – extremely high iron yield – fully utilizing the capabilities of a COREX® Process
- Utilizing the "low cost" export gas from the COREX® plant (compared to expensive natural gas or heavy oil)
- In case other, additional ironmaking plants are within the steel works, also pellets for these plants could be produced. COREX® is producing approx. 13 GJ per ton of hot metal export energy, where "only" 1 GJ/t of pellet is required.

It is possible to realize the overall plant concept in different phases:

Phase 1: COREX® plant, oxygen plant and the "export gas utilization" plant

Phase 2: Integration of pellet plant

After finalization of both phases the full benefits can be realized

Further Advantages of a COREX®/MIDREX™ DR based Ironmaking Route

- High quality hot metal being used in the EAF providing the following advantages
  - Decrease of the EAF electric power consumption
  - Decrease of the EAF electrode consumption
  - Increase of the EAF productivity
  - Less dependency from scrap quality
- Charging of hot DRI further decreases EAF electric power consumption and increases the EAF productivity
- Lowest carbon consumption per ton of metallic iron resulting in low CO_2 emissions

3.1. Single Plant Production Capacity Estimates

Table 1: Main production data

		Alternative 1	Alternative 2
	Unit	Corex_CCPP	Corex_DR Plant
Plant Capacities			
Pellet Plant	t/a	1.857.000	3.626.400
COREX	t/a	1.500.000	1.500.000
Combined Cycle Power Plant *)	MW_{el}	272	-
DR Plant	t/a	-	1.237.347
Export Gas after DR plant **)	MWhth/a	-	833.175

*) Based on the assumption the complete available thermal energy from COREX® is converted into electrical power with an efficiency of 46%

**) No electric power plant was assumed for the DR export, as the remaining export gas could be used in an adjacent steel plant – power plant capacity would be approx. 45 MWel in case the complete available thermal energy from the DR export gas is converted into electrical power with an efficiency of 46%

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3.2. Investment Cost

Based on the fact that investment costs differ from location to location, only the operation costs are estimated in this comparison. For a full production cost calculation the following single plants should be considered in the investment cost calculation:

- Ironmaking
  - Raw material storage
  - Pelletizing plant
  - C-1.5M COREX® plant
- Power plant (Alternative 1) or MIDREX™ DR plant (Alternative 2)
- Oxygen Plant (outsourcing possible)

3.3. Pellet, Hot Metal, DRI and Electric Power Operation Cost Estimate

3.3.1 Hot metal operation cost estimate for Alternative 1

Hot metal operation cost estimate for Alternative 1 are detailed in Figure 13.
Basis for the operation cost estimate is a COREX® plant with raw material cost in February 2016.

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Table 2: COREX® hot metal operation cost estimate for Alternative 1

Production:		1.500.000	t HM	8.300	h/a
Cost type		Unit	cost / unit USD	Consumpt. / t HM	cost / t HM
Material cost	**100%**			1,534	
Lump ore 58%	17%	t	40,68	0,266	10,82
Pellets (calculated)	81%	t	57,24	1,238	70,86
Mill scale	2%	t	50,00	0,030	1,50
Limestone		t	10,00	0,090	0,90
Dolomite		t	10,00	0,189	1,89
Sludge (75% to be recycled to pellet plant)		t	-60,00	0,030	-1,80
Credit slag		t	5,00	**-0,393**	-1,97
Sub total material					**82,20**
Energies					
COREX-gas credit		MWhth	0,00	-3,486	0,00
Losses COREX-gas credit - availability		MWhth	0,00	0,021	0,00
COREX-gas for coal drying		MWhth	0,00	0,111	0,00
Fuel	72MJ	MWhth	0,00	0,020	0,00
Coal A1		t	55,30	0,450	24,89
Coal A2		t	50,00	0,450	22,50
Coal briquetting	50%	t	13,63	0,500	6,82
Nut Coke		t	85,72	0,098	8,40
Oxygen		m³	0,007	506,000	3,72
Nitrogen		m³	0,013	90,000	1,15
El. Energy (internal production)		kWh	0,005	85,000	0,41
Sub total energies					**67,89**
Other operating supplies, personnel					
Other operating supplies, personnel		Manyear	30.000	60 pers.	1,20
Personnel, maintenance&mat.handling		Manyear	30.000	20 pers.	0,40
Raw Material Handling		USD/t mat.	1,00	3,311	3,31
Industrial water		m³	0,50	1,500	0,75
Refractories for COREX		kg	1,00	1,500	1,50
Maintenance (% of investment)		%	2,0%	1,000	4,27
Maintenance (USD/t)		USD/t	0,00	1,000	0,00
Others (% of other operating supplies)		%	5,0%		0,57
Sub total other operating supplies, personnel					**12,00**
Total operation cost per ton of HM (Alternative 1 with own power production)					**162,1**

3.3.2 DRI operation cost estimate for Alternative 2

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Table 3: COREX® gas based MIDREXTM DR plant DRI operation cost estimate for Alternative 2

Production:		1.237.347	t DRI	8.200	h/a
Cost type		Unit	Cost / unit USD	Consumpt. / t DRI	Cost / t DRI
Material cost				1,430	
Pellets	100%	t	64,22	1,390	89,26
Credit sludge		t	-60,00	0,030	-1,80
MgO		t	1.000,00	0,001	1,00
Sub total material					**88,46**
Energies					
Fuel		MWhth	3,87	3,472	13,43
DR-gas credit		MWhth	-3,87	0,555	-2,15
Electric energy		kWh	0,085	150,000	12,75
Sub total energies					**24,03**
Other operating supplies, personnel					
Personnel, operating		Manyear	30.000	100 pers.	2,42
Personnel, maintenance & material handling		Manyear	30.000	50 pers.	1,21
Industrial water		Nm³	0,50	1,500	0,75
Raw Material Handling		USD/ t mat.	1,00	1,390	1,39
Maintenance (% of investment)		t	3,0%	1,000	5,46
Others (% of other operating supplies)		%	5%		0,56
Sub total other operating supplies, personnel					**11,79**
Sub total operation cost t DRI					**124,28**

Remarks:

- COREX® hot metal operation cost are based on no credit for COREX® export gas. Consequently no cost for export gas in downstream utilization is applied resulting in low operation cost for the downstream products i.e. electric power (Alternative 1) and DRI (Alternative 2). The real indicator for the economics for any alternative is the IRR or ROI and not the hot metal or DRI operation cost estimate.
- Hot metal operation cost in Alternative 1 are lower compared to Alternative 2, as in Alternative 1 the electric power operation cost are derived from the operation cost of the own power plant, whereas in Alternative 2 an external power source which is typical higher in price, is assumed.
- Fuel cost in the DR plant calculation is based on a respective COREX® export gas treatment to be suitable for the DR plant operation.

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3.3.3 Summary operation costs for Alternative 1 and 2

Table 4: Summary operation costs for Alternative 1 and 2

		Alternative 1	**Alternative 2**
Operation Cost Estimate			
HM	USD/t	162,1	193,0
Hot metal cost based on a gas credit for Corex gas of	USD/MWhth	0,0	0,0
Hot metal / DRI cost based on a electric power price of	USD/kWh	0,005	0,085
Electrical Energy (own production)	USD/MWh	4,9	-
Electric energy cost based on COREX export gas cost of	USD/MWhth	0,0	-
DRI	USD/t	-	124,3
based on fuel gas cost after Corex export gas treatment of	USD/mmBTU	-	1,07
DRI cost based on a electric power price of	USD/kWh	-	0,085
Export Gas after DR plant	USD/MWhth	-	0

For Alternative 1: Hot metal is produced at USD 162,1 / t_{HM} (considering no credit for the export gas) and additionally electric power of 272 MW_{el} is produced.
For Alternative 2: Hot metal is produced at USD 193,0 / t_{HM} (considering no credit for the export gas) and DRI is produced at USD 124,3 /t_{DRI} and additional surplus export gas available for downstream use.

3.4. Economical Conclusions

It is understood, that a complete economic evaluation with CAPEX and OPEX depends on many factors e.g. raw material costs, energy prices, export gas revenues which may also change from location to location.
The operation cost in the above table shows that a COREX® gas based hot metal and steel production with combined power production and/or DRI production are highly competitive compared to the traditional iron making.
In areas with existing DR plants with high natural gas price or low natural gas availability, the feature of the COREX® export gas production as a “by-product” is even more attractive as investment cost will decrease dramatically as at existing DR plants the natural gas can be substituted by COREX® gas with low investment.

4. OUTLOOK

Based on the successful experience of the operating Corex plants, further considerable knowledge base has been accumulated during the recent years with respect to engineering and operation.
Considering all factors for an investment decision for the iron and steel industry it is shown, that plant concepts based on COREX® technology and downstream gas utilization are highly competitive in a rapidly changing and challenging environment due to:

- Integrated plant concepts and energy solutions
- Raw material flexibility and waste material utilization
- Environmental consideration
- Attractive economic key figures for total investment
- Available module sizes to meet customer requirements for plant capacity