DC Arc Furnace Technology Applied to Smelting Applications

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ABSTRACT

DANIELI CentroMet has developed a unique DC technology especially suitable for melting of prereduced iron, a concept that also should be suitable for smelting applications.

The furnace concept offers a more compact furnace design as compared to traditional submerged arc furnaces due to the operation at higher impedance and an increased flexibility with respect to the use of various types of charge materials. The furnace operation does not require the same control of the burden resistivity and gas permeability as is the case with the traditional submerged reduction furnace. Ore fines can be used without pelletizing and ferroalloy fines can be remelted. The furnace operation can also easily be switched over from production of one ferroalloy grade to another.

The energy loss from the submerged arc process is lower compared to the open arc process. The more compact furnace design, the higher power density and the far lower electrical loss in the furnace secondary system compensate for this increased energy loss. The compact design makes it easier to seal the furnace for improved energy recovery from the process gases.

The furnace can be designed with one, two or three electrodes, depending on the actual smelting process and the required power.

The conductive bottom is designed with conductive refractory material or, as an alternative, with water-cooled anodes as for steel making applications
The mechanical design of the furnace can be identical to the steelmaking furnace, i.e. tiltable shell with swingroof or with non-tiltable shell as for the traditional reduction furnace. The "steelmaking" design offers the possibility to use an exchangeable shell for increased flexibility and reduced downtime for refractory maintenance.

In principle, except for processes which involve compounds with high vapor pressures, the proposed furnace technology can be used for the majority of reduction processes where submerged arc furnace technology is used today.

1. INTRODUCTION

Ferroalloys are used primarily in the steel industry for reduction, deoxidation and alloying to achieve the required chemical and physical properties for the final product. Manganese is used in virtually all commercial steel grades, silicon in most grades and chromium in all stainless grades. Molybdenum, nickel, vanadium, titanium, boron and niobdenum, colombium and calcium are also frequently used. Aluminum is used in most steel grades, but aluminum and ferroaluminum are not considered as ferroalloys.

The ferroalloys are added as either iron-based master alloys, carbides, oxides or the base metals.

Most iron-based or carbide alloys are produced by carbothermic reduction of oxides in electric smelting furnaces. Some alloys are produced by using aluminum or silicon as reductants. Such reactions are strongly exothermic consequently there is no need for any additional electrical energy supply. However, production of silicon and aluminum require significant electrical energy, therefore the net energy source is electricity.

The ferroalloy production is consequently concentrated not only in countries with mineral resources but also to countries with low cost electrical energy.

2. THE SUBMERGED SMELTING FURNACE

The major ferroalloys, Si, Mn and Cr are all produced by carbothermic processes. All silicon is produced in the conventional submerged furnace. Ferromanganese with low Mn content can be produced in a blast furnace, while the majority of the ferromanganese is produced in the submerged furnace. Most ferrochromium is processed in the submerged furnace but a significant volume is also produced in the single electrode DC furnace at Samancor, RSA, the Plasmarc process.

The submerged furnace is principally a counter-current reactor where the carbon monoxide from the reduction process passes through the burden. The charge is preheated and to some extent prereduced. The energy consumption is close to that theoretically expected for the actual smelting process.

The heat generation by the supply of electrical energy to a submerged furnace is distributed between direct arcing, current passing between the electrodes and between the bath and the electrodes. The charge mix must therefore be controlled to give the correct resitivity. This is a severe limitation, mainly for the carbon reductants but also for the slag chemistry in slag processes.

Too much fines in the charge mix can create problems with pressure buildup with a risk for random process behavior, increased energy consumption and decreased metal yield. Too much coarse material can create problem with reduced contact between the carbon monoxide and the charge.

A submerged furnace should preferably be operated with lumpy ore or high quality pellets or briquettes. Most of the mineral deposits used today require mineral processing and consequently an agglomeration process before use in the submerged furnace.

Successful use of fine material in submerged processes are reported from pilot plant trials with FeSi smelting in a 2 MVA single electrode DC furnace. Up to 20 % of the raw materials were fed as sand and millscale through a hollow electrode.[1] Such feeding system is except for CaC_2 smelting not used for submerged arc furnaces.

The submerged furnace can be characterized by:

- low energy consumption
- low power density, some 300 kW/m^2 hearth area for a FeCr furnace
- low impedance, some $2 * 10^{-3}$ Ohm for a FeCr furnace

3. PLASMA FURNACES

The need to use low-grade mineral deposits and consequently ore processing is the driving force for development of plasma processes. During the years a number of processes have been developed but only two of them are used for commercial large-scale production of ferroalloys. Smaller plasma furnaces are used for special smelting applications.

SKF Steel in Sweden has developed a Plasma Furnace for various smelting applications.[2] Two large-scale commercial units are commisioned, Plasmachrome in Malmö, Sweden and Plasmadust in Landskrona, Sweden. The Plasmachrome operation is discontinued while the Plasmadust, Figure 1, still is in operation.

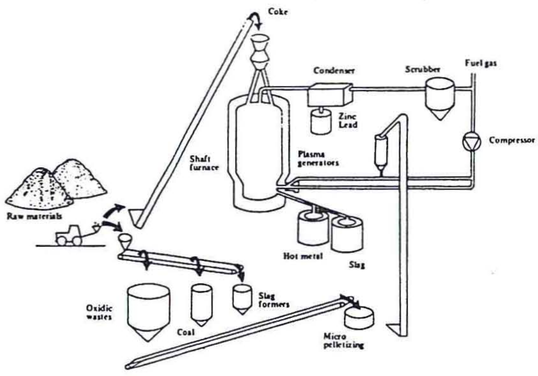

Figure 1. Principle flowsheet for Plasmadust

The plasma furnace is a coke filled shaft furnace where metal fines are injected into the lower part of the shaft. The injection is integrated with the plasma torches used for heat generation. The electrical energy consumption is high compared to submerged arc furnaces. The concept is based on the use of fines and on recovery of the energy in the off gas. No major technological problems are reported with the operation.

The Plasmarc process, where ore fines, reductants and slag additives are charged through a hollow electrode in a single electrode DC furnace, originates from the ELRED trials by ASEA in the early seventies Figure 2.[3]

The Plasmarc furnace is more compact compared to the submerged furnace. The power density is higher, some 600 kW/m^2 and the furnace operates with higher impedance, some 5 * 10^{-3} Ohm.

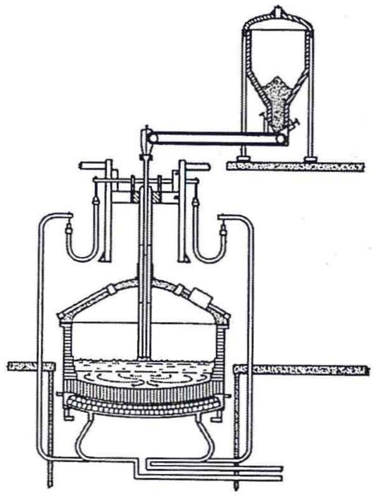

Figure 2. Schematic view of the ELRED furnace

The furnace concept was developed into a chromite smelting process by the work at MINTEK, RSA, in the late seventies and early eighties. The first commercial operation started with a 16 MVA furnace at Middleburgh Steel, RSA, in 1984. The furnace was upgraded to 40 MVA a few years later. Samancor, RSA, is presently operating two Plasmarc furnaces.

Unlike the submerged arc furnace, the PLASMARC furnace is an open bath process. Consequently, compared to the submerged arc furnace, the energy losses are far higher; typically higher by some 1000 kWh per ton of charge-chromium. This higher energy consumption is compensated for by the use of fines, higher chromium yield, the ability to remelt metal fines and an overall better raw materials flexibility.

The material feeding system adds some limitation to the process. The slag chemistry must be carefully controlled to avoid clogging. Excessive slag foaming can also create feeding problem. The change of the graphite electrode is complicated and reduces the furnace productivity.

The chromite smelting is a carbon saturated process. The bottom anode can therefore be based on carbon as the conductive media. Electrically conductive magnesia-carbon bricks with metal sheets between the bricks build up the bottom. The bottom lasts for several years without repairs. This can be compared to the 500-1000 heats for the same anode concept used for steelmaking applications. The reason for the short life for steelmaking application is the far higher oxygen potential, frequent bottom exposure to slag and air and the temperature fluctuations caused by the batch operation.

4. THE DANIELI TWIN ELECTRODE DC FURNACE

The DANIELI CENTROMET Arc Furnace concept is based on experience acquired since 1970 in the design and manufacturing of equipment for electric steel making. The furnace concept includes not only the furnace itself but also all auxiliary equipment required for the utilisation of modern process technologies.
A recent development in the DANIELI DC EAF technology is the Twin Electrode DC EAF concept.

At HYLSA, Flat Product Division, Monterrey, Mexico a DANIELI 135 tonnes Twin Electrode DC EAF with an installed power of 208 MVA was started up October 30, 1998, Figure 3. The furnace is designed for melting 100% DRI charge.

The maximum power density is 4300 kW/m^2 while the normal power density is 3000 kW/m^2. The typical operating impedance is $8 * 10^{-3}$ Ohm.

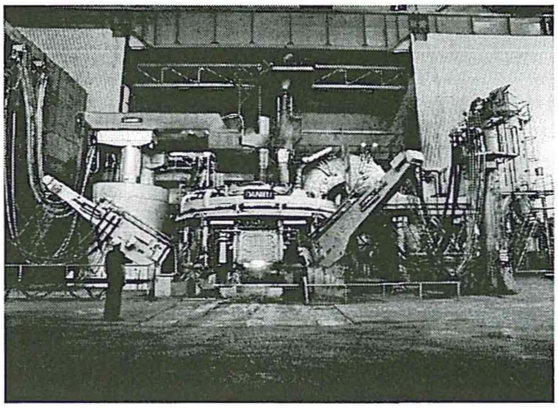

Figure 3, the Twin Electrode DC EAF at HYLSA

Conventional DC furnaces for steel melting application have only one electrode. The main features of the twin electrode concept are:

- reduced electrode consumption
- arc deflection towards the furnace center.

The consumption of graphite electrodes is mainly a result of side oxidation and tip wear. A recent update of the empirical relationships by Bowman indicates only minor differences in specific tip consumption between AC and Single Electrode DC applications.[4] For the prediction of electrode consumption Bowman suggests the following formulae:

AC furnaces

$$W_{EAC} = \frac{3}{TPH} * \begin{bmatrix} k_{OX} * \pi * k_{ED} * D_E * L_{OX} + \\ 0.013 * I_{EAC}^2 * t_U \end{bmatrix} \quad (1)$$

DC furnaces, single electrode concept

$$W_{EDC} = \frac{1}{TPH} * \begin{bmatrix} k_{OX} * \pi * k_{ED} * D_E * L_{OX} + \\ 0.0124 * I_{EDC}^2 * t_U \end{bmatrix} \quad (2)$$

where

W_{EX} = Electrode consumption, X=AC and DC respectively, kg/t

TPH = Production, t/h

k_{OX} = constant depending on oxygen blowing practice.

$$k_{ED} = \frac{D_E + D_{TIP}}{2D_E}$$

D_E = Nominal electrode diameter, m

D_{TIP} = Electrode tip diameter for electrode in “steady state” condition, m

I_{EX} = Electrode current, X=AC and DC respectively, , kA

t_U = Time utilisation factor, power on/tap-to-tap

For the case of a multiple electrode DC furnace however, equation (2) can be written

$$W_{EDC} = \frac{N_E}{TPH} * \left[\begin{array}{l} k_{OX} * \pi * k_{ED} * D_E * L_{OX} + \\ 0.0124 * \left(\frac{I_{EDCT}}{N_E} \right)^2 * t_U \end{array} \right] \quad (3)$$

where

N_E = Number of graphite electrodes

I_{EDCT} = Total electrode current, kA

A fair comparison of various EAF concepts should be based on some common conditions with respect to tap-to-tap time and installed power.

Since the productivity, TPH, is dependent on power, charge weight and energy requirement, the calculation of anticipated graphite consumption could be based on the following:

p_{SARC} = specific arc power kW/t to be equal (700 kW/t)

P_{ARC} = AC arc power equal to DC arc power

ttt = tap-to-tap time to be equal

t_U = time utilisation to be equal

V_{DCAC} = fix relation between DC arc voltage and AC arc voltage, $U_{DC} = 1.5*U_{AC}$

U_{ADC} = selected DC arc voltage being a function of DC current

D_E = electrode diameter being a function of electrode current

Based on the conditions above, the electrode consumption has been calculated and compared with the consumption for modern High Impedance EAF’s. The result is shown in Figure 4.

The corresponding arc power and electrode current is shown in Figure 5.

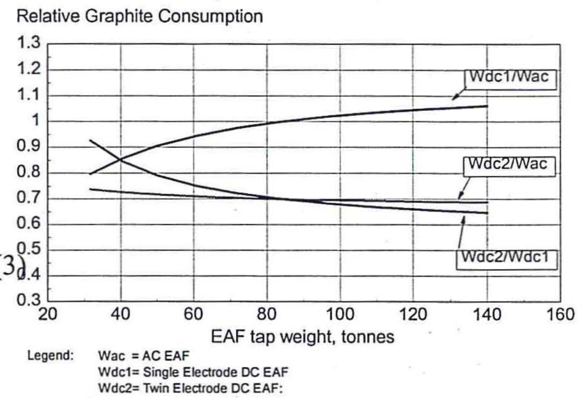

Figure 4. Relative electrode consumption as function of EAF tap weight

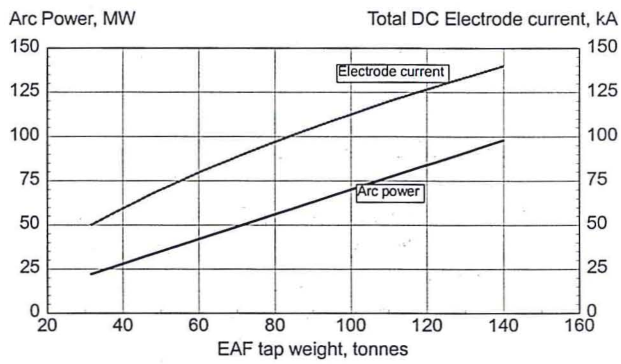

Figure 5. Arc power and total DC electrode current as function of EAF tap weight

The twin electrode concept has lower electrode consumption than both the conventional AC furnace and the single electrode DC furnace at high power input.

The EAF current conducting system is influenced by electromagnetic forces, which are created by the current in adjacent conductors. For the case in which the current in adjacent conductors flows in the same direction, this force will tend to pull the two conductors towards each other. However, in the case in which the current flows in opposite directions, the two conductors will tend to be pushed away from each other; see Figure 6.

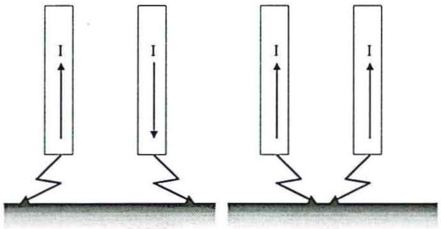

Figure 6, arc deflection.

The forces acting on parallel conductors with the length L and at a distance "a" from each other can be calculated:

$$F = L * \mu/(2*\pi*a) * i_1 * i_2$$

where

L	= length of the conductor
a	= distance between the conductors
μ	= magnetic permeability
i_j	= instantaneous current value

The consequence of this relationship for the conventional three electrode AC furnace is a deflection towards the slag line. This can create problems not only by excessive slag line wear but also mechanical stresses on the electrode including the arms and masts.

In a single electrode DC furnace the arc deflection is a function of electrode current and the magnetic flux generated by conductors adjacent to the arcing zone. By a proper routing of the conductor arrangement underneath the furnace bottom it is possible to minimize the magnetic flux in the arcing zone and thereby ensure a vertical arc and consequently no hot spot zone.

In the case of a twin electrode DC configuration however, the two arcs will be deflected towards the furnace center. Continuous feeding of charge material into the arc zone favors a fast melting and will also limit the superheating of the melt.

The bottom anode concept for a steelmaking furnace must be designed differently to a smelting furnace. The discontinuous steelmaking operation with large temperature variations, frequent exposure to aggressive oxidized slag and frequent direct contact between the metallic charge and the conductive bottom reduces the bottom life compared to a smelting furnace.

The DANIELI anode design is optimised for steelmaking. The most important requirements on a bottom anode design could be summarised as follows:

- Long campaigns between maintenance
- Easy and swift maintenance
- Quick start up procedure in cold condition
- Quick start up procedure in hot condition after bottom inspection
- Capability to withstand intense oxygen injection into the melt
- High current conduction capacity
- Reliable, consistent and safe operation
- Possibility to supervise anode current conduction conditions
- Possibility to continuously supervise the anode thermal condition

In a high productivity unit it is of importance to limit maintenance of the anode(s) to periods with scheduled shut downs not related to the anode itself, e.g., in combination with slag line repair.
Having the above mentioned design criteria in mind DANIELI decided to develop a water-cooled bottom anode, figure 7. After a research and development stage, which included theoretical calculations, simulations as well as laboratory tests, the selected solution was installed in an

industrial scale plant at the Balboa Steelworks in Spain.

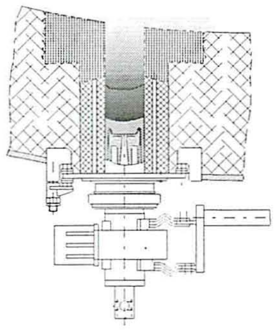

Figure 7. The DANIELI water-cooled bottom anode

The bottom anode system comprises four water-cooled anodes embedded in the refractory lining. The anode is built with an upper part made of steel and a lower copper part, welded to the steel part. The lower copper part is with a tubular section and an inner top surface machined to form fins, arranged in a spiral configuration. This ensures a high water velocity over the entire surface, which together with the contribution from the fins results in a high heat transfer capacity.[5] .

So far, the performance with this anode design is better than expected. The power on time between the replacement exceeds 3000 hours for the HYLSA installation as compared to 500-1000 hours for any alternative design.

5. CHROMITE SMELTING IN A TWIN ELECTRODE DC FURNACE

The possibility to use a modified twin electrode concept for smelting applications has been studied. The furnace and process concept have some similarities to the present operation of the PLASMARC process. The PLASMARC concept is based on continuous feeding of material through a hollow graphite electrode. This favors a good recovery of fines but the system also adds some restrictions to avoid clogging in the electrode.

The experience with feeding 100 % hot DRI directly into the arcing zone between the two electrodes in the HYLSA furnace is promising. The observations so far do not indicate more dust losses as fines as compared to batch charging. The furnace operates close to equilibrium and there is no sign of losses due to insufficient reduction of the DRI.

Chromite and DRI is entirely different and the kinetics for chromite reduction must be further evaluated. The power density for the HYLSA furnace is far higher compared to the PLASMARC process. The residence time for the charged material is consequently shorter.

Recent studies at the Royal Institute of Technology in Stockholm [6,7] on reduction of chromiumoxide in liquid slag with carbon shows not only that the slag viscosity and the temperature have the expected influence. More interesting is the conclusion that addition of metal, preferably carbon saturated, increases the reaction rate. The difficulty of nucleation of solid chromium results in an incubation period. Once a liquid metal phase is formed or introduced the incubation time can be shortened or eliminated. Remelting metal fines should consequently improve the reaction kinetics for chromite in processes where the main part of the reduction takes place in the slag phase.

The energy balance for a hypothetical chromite smelting operation in the HYLSA Planos furnace can illustrate the use of the DANIELI twin electrode DC furnace for smelting application.

The calculation is based on following assumptions:

- There are no process limitations. This assumption is necessary for the calculations and must be studied in future pilot and full-scale trials.

- The raw materials composition is shown in Table 1.

	Cr_2O_3 %	FeO %	SiO_2 %	CaO	Al_2O_3 %	MgO %	C %
Chromite	50.0	25.0	5.0	1.0	10.0	9.0	
Carbon		0.9	6.2	0.9	2.7	0.9	88.5
Lime			10.0	90.0			

Table 1. Raw materials composition

- The dust generation is 5 % of the charge except for elements forming species with high vapor pressure and for carbon. This is more than observed in HYLSA.

- The slag is reduced to 3.8 % Cr_2O_3. The slag contains 2 % metal as immersed droplets.

- The furnace is operated at a temperature some 30 C over the estimated slag liquidus temperature.

- The furnace is closed.

- The slag from the chromite must be fluxed. Lime and SiO_2 can both be used to flux the actual system. Lime is used to minimize the SiO_2 content to avoid energy consumption by reduction of SiO_2.

Figure 3 shows the system boundary.

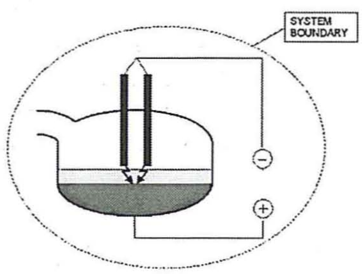

Figure 8. System boundary

Table 2 shows the global materials balance. The dust is calculated as dust collected in the bagfilter. Mg(g) and SiO(g) leaving the furnace are oxidized to MgO and SiO2 respectively. The Cr yield is 91.9 %.

	kg	% Cr	% C	% Si	% Fe		
Metal	10000	56.7	7.2	2.3	33.8		
Metal, slag	11	56.7	7.2	2.3	33.8		
		% Cr2O3		% SiO2		% Al2O3	% MgO
Slag	569	3.8		12		35	28
Dust	131	35	33	10		5	12

Table 2. Materials balance

Figure 9 3 shows the energy consumption for the smelting reactions.

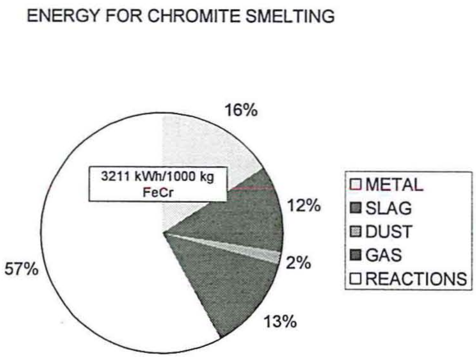

Figure 9. Energy consumption for the smelting reactions.

Figure 9 does not include the furnace losses. The measured losses to the water-cooled parts of the HYLSA furnace are shown in Table 3.

	Water m3/h	DT C	Q MW
Roof	950	8	8.8
Wall	1070	4	5.0
Anodes	160	0.3	0.1

Table 3. Losses to water-cooled parts in the HYLSA furnace

These losses are measured for the normal HYLSA operation, continuous feeding of DRI at flat bath conditioning and 1550 °C steel temperature. The assumed operation temperature for chromite smelting is 1750 °C. The major part of the loss is by radiation from the bath. The losses to the roof and wall can be estimated:

$$Q = Q_{DRI} *(2023/1823)^4$$
$$Q = Q_{DRI} * 1.5$$

The losses from the refractory shell are some 1 MW. The total thermal losses for chromite smelting is:

$$Q = 21.7 \text{ MW}$$

The losses in the power supply system are controlled by the current:

$$Q = I_s * \Sigma R_s + I_p * \Sigma R_p$$

where

I_s = current on the transformer secondary side
ΣR_s = sum of the individual resistances on the secondary side
I_p side = current on the transformer primary
ΣR_s = sum of the individual resistances on the primary side

The loss for the Hylsa furnace is 6.0 MW for 150 kA. The corresponding power is 96 MW. The main part of the losses is caused by the resistance in the electrodes.

Total furnace losses:

$$Q_{tot} = 27.7 \text{ MW}$$

Table 4 shows the productivity and consumption of electrical energy.

Base 1000 kg chargechromium		
Smelting	3211	kWh
Power	96	MW
Electrical loss	6	MW
Thermal loss	21.7	MW
Productivity	21.3	1000 kg/h
Electrical energy	4513	kWh

Table 4. Energy consumption, no preheating

This electrical energy consumption is some 500-1000 kWh higher as compared to most submerged operations. Figure 10 shows the annual output for some chromite smelters.[8] The regression fits exactly to 3800 kWh/1000 kg FeCr assuming typical values for availability and power factor.

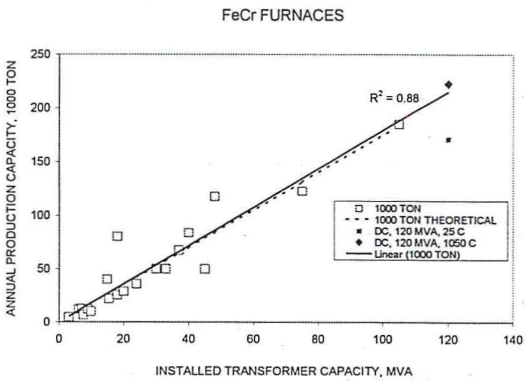

Figure 10. Production capacity for FeCr smelters.

The higher electrical energy consumption for the described furnace concept is to some extent compensated for by the increased raw materials flexibility, the use of raw materials fines and a high Cr yield. The furnace concept also offers good possibilities for charging preheated and prereduced material.

The huge amount of CO gas leaving the furnace can be used for prereduction and preheating. Figure 11 show the equilibrium conditions for prereduction of chromite. The reduction of chromite starts at some 900 °C. The electrical energy consumption for a charge preheated to 75 % of the equilibrium conditions at 1050 °C can be estimated to some 3400 kWh, Table 5.

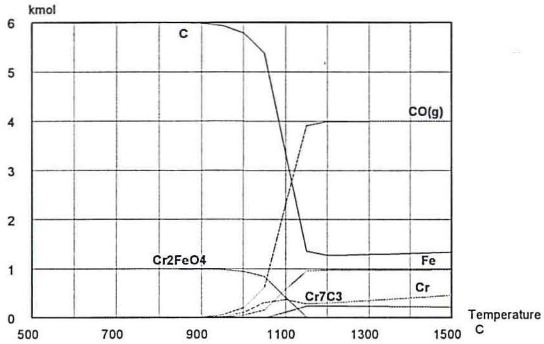

Figure 11. Equilibrium for chromite reduction.

Base 1000 kg chargechromium		
Smelting	2431	kWh
Power	96	MW
Electrical loss	6	MW
Thermal loss	21.7	MW
Productivity	28.1	1000 kg/h
Electrical energy	3421	kWh

Table 5. Energy consumption, preheating to 1050 °C.

6. CONCLUSIONS

The energy consumption in an "open arc" furnace for smelting applications, similar to steel melting practice, is higher compared to the traditional submerged arc process. This is a result of heat losses to water-cooled roof and side wall panels typically used in furnaces designed for steel making.

The DANIELI Twin Electrode DC concept however, provides some specific features that can compensate for this. Based on the excellent performance when melting continuously charged DRI the following features can be identified:

- Compact mechanical design requiring minimum space
- High productivity due to high power density, 4-5 MW/m^2
- Arcing zone concentrated in furnace center providing quick melting of continuously charged materials
- Flexibility in accepting various charge materials on form of lump or fines
- The ferroalloy composition can easily be changed to meet changed market demand.
- More simple and faster control of the process compared to submerged arc operation

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