European Commission

technical steel research

Direct ironmaking via rotary hearth furnace and new smelting technology

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Contract No 7215-PP/060
1 July 2001 to 31 December 2004

Final report

Directorate-General for Research

2007 EUR 22826 EN

Cataloguing data can be found at the end of this publication.

Luxembourg: Office for Official Publications of the European Communities, 2007

ISBN 92-79-05447-1

ISSN 1018-5593

Printed in Luxembourg

PRINTED ON WHITE CHLORINE-FREE PAPER

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1 Final summary

1.1 Objectives of the project

The aim of the project is to develop and test a new two-step ironmaking process based on:

- Iron bearing materials pre-reduction in a Rotary Hearth Furnace (RHF)
- Smelting of the hot pre-reduced iron (Directly Reduced Iron, DRI) in a coal- and oxygen-blown converter (New Smelting Technology, NST)

The main target of the project is the design, construction and testing of a demonstration plant of a size large enough to provide experimental results directly transferable to the commercial size.

Further objectives of the work are:
- To develop oxygen / coal blowing and hot DRI charging techniques for optimum smelting and for hot metal pre-refining inside the smelter
- To verify the productivity and reliability of the plant
- To develop techniques to avoid polluting emissions in a process that utilises waste materials from iron/steel making integrated plants

The new process has been conceived to have a cost-effective and environmental-friendly technology.

Cost reduction key-points
- The process does not require any prepared charge
- Electrical energy is not needed, because the DRI smelting is made just using chemical energy
- The productivity of the smelter is high, which means limited investment cost

Environmental key-points
- The process can use practically all the residues coming from the steel making route (including sludges and oily mill scales), solving the increasing problem of steel wastes treatment
- The off-gas coming from the smelter is used as a fuel in the RHF, with optimisation of the overall energy utilisation and consequent reduction in energy consumption

Therefore *the key expected benefits of the new process are: waste recycling, reduced energy consumption, low investment and production cost.*

With a capacity range between 0.1 and 1.0 million tons per year of hot metal production, the new process has not been conceived to compete against the Blast Furnace in large-scale integrated mills, but it has been mainly designed for two basic applications:
- To convert iron-bearing by-products into valuable metals. In this case the hot metal production is related to the amount of wastes that must be treated.
- To produce hot metal at low-mid scale size (typically around 500,000 tpy), in order to match with modern mini-mill architectures (hot metal used as valuable scrap substitute).

1.2 Initially planned activities and work accomplished

The activities initially planned for the project are described in the contractual technical annex (Annex A).

The work accomplished during the development of the project is in line with the initial programme,

The delay to complete all the work foreseen for the project has been mainly consequence of the following reasons:

1. Due to a modification in the regulations occurred in August 2001, it was necessary to follow a longer and more complicated procedure to obtain the permits for building the plant. This procedure caused a delay in the availability of the area selected for the plant and the starting of erection activities had to be postponed of six months (the erection started in October 2002 instead of April 2002).
   To limit and recover this delay the partners defined a detailed planning and organisation of the trials, in order to minimise any future undesired stoppage:
   - Tests of short duration performed on three shifts (instead of one shift originally foreseen)
   - Personnel exclusively dedicated to the demonstration plant
   - Capital spare parts included in plant supply

2. During the first operating period (RHF tests, July ÷ December 2003) some problems were encountered in different sections of the plant. Each solution was identified step by step during the trials and the relevant modifications to the equipment were carried out without shutting down the plant, during maintenance stoppages. This first operation phase made clear to the partners that the average time to carry out the necessary modifications to the plant was around one week – 10 days. This is due to the fact that even being a demonstration plant, all the equipment installed is of an "industrial" size and any modification, even if conceptually simple, takes time.
   After this phase it was also clear that in order to minimise any undesired stoppage during operation it was fundamental to have a constant technical plant assistance, to identify immediately the modifications necessary to the plant and to solve the problems possibly encountered during the operating phases. For this reason the coordinator asked the Commission to place a subcontract to get a full-time support during the whole period of tests.

3. During the start-up of the smelter (first pre-heating, December 2003) an unexpected significant problem was encountered to the refractory and due to this problem it was necessary to postpone the first smelting.
   At this point it was clear to the partners that the time schedule was really too compressed and that a prolongation of the project would be fundamental to finalise the objectives of the project, especially the ones regarding the smelter unit. For this reason the partners asked that the project was extended of six months beyond the original termination date (30-06-2004). The Commission granted the new completion date: 31-12-2004.
   The prolongation of the project was also fundamental to solve the last critical point still open for the DRI production: the sticking behaviour of the wet green pellets.
   The additional six months available for the project, in fact, made possible to install and test a dryer for the green pellets (between the pelletising disc and the RHF vibrating feeder). The dryer have facilitated the continuous operation of the plant, solving all the plant interruptions due to the sticking problems. A continuous operation of the RHF was considered a very important target, especially to finalise the objectives of the PHASE II of plant operation, where a long-term operation is needed.

4. In the period between February and December 2004 tests of short duration were carried out (the plant was shut down in August, for summer holidays, and in November for the installation of the new dryer for the green pellets).
   The tests of long duration could not be carried out as scheduled, because some key components of the smelter could not reach satisfactory performances even during tests of short duration (few shifts). The

following problems have been faced and some solutions have been identified to complete the programme with the long duration tests:

- Due to the critical slag conditions, especially during the transient periods when big fluctuations in FeO content may happen, the refractory lining in the slag area showed a quick erosion rate. To solve this problem a new refractory (castable type) was identified, but, as described in the annex H, also this material was not able to solve the problem .
- Due to the big thermal capacity of the tapping siphon, it was difficult to keep the hot metal and the slag in the liquid state. To solve this problem it was decided to simplify the tapping system and tap metal and slag on a batch basis.
- The coal injection system showed a number of problems, which caused a limited operability range. Several changes were introduced to the system and some improvements could be reached, but the instability of coal injection remained the main cause of unplanned delays during tests. To further improve the coal injection performances a new type of oxy-coal lance was designed.

Due to the non-conclusive results, the partners decided to continue the test activity beyond the official deadline and test campaigns were planned up in the second half of 2005 and, because of the problem with the new refractory lining, also in the first months of 2006, to complete the programme, The last long duration test was performed at the end of February, 2006.

Even if a great deal of development work has already been done, the partners are aware that much has still to be done before this process may be considered ready for the industrial exploitation of the smelting section.

However, although the new smelting technology in its current stage is not completely proved, the good results already achieved make us optimistic about the future results and the successful completion of the development stage.

1.3 Description of activities and discussion

In the frame of the project the partners have built and tested a demonstration plant in Piombino works (Italy) for the production of hot metal via an innovative two-step smelting reduction process.
The new ironmaking process is based on two production steps: pre-reduction of iron-bearing materials in a Rotary Hearth Furnace (RHF) and smelting of the hot DRI in an oxy-coal converter.
The plant has been designed to process up to 65,000 tpy of feed materials (on a dry basis) with a rated hot metal output of 30,000 ÷ 35,000 tpy.

Picture 1 Overall view of the demonstration plant in Piombino

BRIEF PROCESS OUTLINE (Figure 3)

Materials preparation
Green pellets are prepared from finely ground iron-bearing materials and a carbon-based reductant, such as coal or coke. A wet blend is prepared in a mixer where these materials are carefully dosed with the addition of water and a small quantity of binder (bentonite). The resulting mixture is pelletised on a rotating disk, adding further water. Green pellets are then screened to remove the under-size fraction that is recycled, while the sized product is loaded to a metallic belt dryer.

Green pellet dryer
This dryer has been introduced during 2004, as a part of the development program, with two main targets:

- To avoid sticking problems at the RHF feeding system
- To prevent decrepitation of green pellets in the RHF

The heat required for drying is provided by the same RHF off-gas, with a resulting improvement of the overall energy efficiency of the process.

Rotary Hearth Furnace

Dry green pellets are then charged into the furnace through a vibrating feeder and distributed across the hearth as a uniform layer of one to three pellets.

The furnace side walls, the roof and the hearth are refractory lined to allow an operating temperature up to 1400 °C.

Fuel gas and combustion air are introduced via several side burners, grouped in three control zones. In zone 1 and 2, secondary air may be introduced via separate “air wickets” for the combustion of CO released by the reduction process.

After charging, pellets are quickly heated up to the reduction temperature. Their total residence time on the furnace hearth to reach a final metallisation degree of 70-90% is between 10 and 18 minutes. Depending on the different raw materials properties, the DRI specific production ranges between 60 and 80 kg/m^{2}h.

The DRI pellets are discharged via a water-cooled screw into a chute and then moved by a metallic belt conveyor to the NST smelting furnace.

The off gas leaving the RHF and the dryer is wasted to the atmosphere after post combustion, air dilution, water injection and dedusting through a bag filter.

NST Smelter

The NST furnace is a non-tilting vertical vessel. The bottom part (hearth) is equipped with a siphon taphole similar to those adopted in cupola or mini-blast furnaces. In the demo plant, hot metal is just cast onto sand moulds. Suitable lances are placed at the side walls to inject oxygen and coal. The position and the orientation of these lances are aimed at generating the proper chemical and fluid-dynamic conditions for the process. In particular, the system is designed to enhance the heat transfer between the upper oxidising zone, where the CO post-combustion occurs, and the reducing zone, where FeO direct reduction and other endothermic reactions take place.

Hot DRI is charged by gravity from the top by a water-cooled chute. Lump fluxes are charged via a separate feeding port.

Cooling of the vessel in the slag and metal-slag interface area is done by special copper cooling elements. The roof of the vessel and the off-gas duct are made of water-walls with pipe-to-pipe welding.

BASIC DESIGN OF THE NEW SMELTING UNIT

During the first months of the project the partners discussed and finalised the basic concepts for the design of the new smelter.

A technical survey of comparable alternative iron making technology showed that four major key-points could influence economics and operation of the plant:

- Refractory wear of the smelter
- Post-combustion degree in the vessel
- Heat transfer into the bath
- Yield losses due to carry over of DRI with the off-gas stream.

Some key decisions were soon taken for the design of the smelter:

- A wall-cooling system was designed to prevent the vessel from premature wear in the slag area and to allow certain process flexibility. Water-cooled copper elements penetrate the refractory lining in the slag zone area. The goal of this cooling system is to generate a frozen layer of slag in front of the lining in the slag zone, which stops any further wear in this area.
- Oxygen / coal system: sidewall lances were placed in such a manner that a good heat penetration and a sufficient slag stirring was assured.
- DRI charging system: a newly designed DRI charging chute (triple pipe) should minimise the carry over of DRI with the off-gas and avoid slag build-ups.
- Hot DRI transport system: the hot DRI is transported with a hot conveying system from the RHF to the smelter. This conveying system is based on a continuous concept, allowing additional operational flexibility.

LABORATORY TESTS

The potential waste materials identified inside Piombino works were: pellet fines, BF dusts, BF sludges, mill scales and BOF dusts. Different mixes of these materials were tested at laboratory level, to investigate their characteristics and their behaviour during reduction.

Different trials were carried out in a batch test furnace at the CSM laboratory in Dalmine (BG – Italy) and satisfactory results were obtained. Objective of this activity was to identify the blends and the furnace operating conditions that could be implemented during the operation of the demonstration plant, to reach the required product specifications. The identification of the reference conditions for the demonstration plant was done aiming at the following objectives:

- No intermediate grinding needed (the demonstration plant is not equipped with a grinding unit)
- No decrepitation
- Good mechanical resistance
- Good metallisation
- Adequate C content, residual Zn, etc.

The results obtained during trials proved that the DRI so produced was suitable to be charged into the smelter.

Details of the tests are reported at paragraph 2.2.

THEORETICAL STUDIES

During the first stage of the project some preliminary studies were carried out:

- Investigation of potential waste material sources at LUCCHINI and waste characterisation, as preliminary phase to the laboratory tests.
- Technical evaluation of reduction fundamentals for the above mentioned waste materials and theoretical characterisation of the DRI (chemistry and physical properties)
- Theoretical evaluation of process related issues, characterisation of the slag and the hot metal

During the further development of the project different models have been developed:

- CFD models for the optimisation of the RHF design.
  Even though the RHF is based on an existing technology, the special requirements of this application were taken into account and many details were analysed using advanced software tools. In particular the following studies were performed:
  - CFD study to identify the best arrangement and geometry of the combustion equipment (burners, air wickets, gas wickets, etc), paragraph 2.6.1
  - CFD study to verify the design of the DRI discharging screw, paragraph 2.6.2

- To analyse the causes of the damage suffered by the smelter refractory, a stress thermal analysis of refractory bricks was performed using ANSYS (paragraph 2.6.3). In particular two main factors were studied: the design of the brick and the methodology used during erection. The study proved that the original design of the brick was not adequate to the actual operating conditions of the smelter. A new brick was designed (and verified) and it was installed during the stoppage planned for the erection of the green pellets drying system.

- Data collected during different campaigns have been used to carry out, for each significant test, two different types of material and energy balance, implemented in 1-D model (paragraph 2.6.4) and supported by CFD simulations implemented by 3D fluid-dynamic simulation tool (paragraph 2.6.5), in order to define and set the parameters relevant to the RHF direct reduction process.
  The "1-D" model program carries out one-dimensional thermal calculation along the furnace length, aiming at analysing on a local basis the parameters of the reduction process and to simulate alternative operating conditions.
  The 3D CFD model is used to make three-dimensional simulations, in order to tune the 1-D model and to characterise the fluid-dynamics of burners and air/gas wickets.

DESIGN, CONSTRUCTION AND ERECTION OF THE PLANT

The activities regarding the design, construction and erection of the plant started at the very beginning of the project and were completed in 2003.
In the first semester of the project the basic choices regarding the new smelting unit had been performed. By the end of December 2001 the activities regarding the basic and detail engineering of the demonstration plant were developed and completed, for each functional unit of the plant (Raw materials preparation, Rotary Hearth Furnace, Hot DRI transport system, Smelter, Off-gas system, Fluids, Civil works and buildings, Electrical equipment, Instrumentation and automation system).
Year 2002 was almost exclusively dedicated to all the activities preliminary for the erection of the plant: procurement, manufacture and delivery of the equipment.
The civil works started in September 2002 and the erection in October.
The erection activities were completed in June 2003 for the RHF section and in September 2003 as regards the smelting section.

COLD TESTS AND START-UP OF THE PLANT

Before the start-up of the plant the operating personnel was trained through a dynamic plant simulator.
The plant simulator is an advanced software package, which is able to provide a realistic environment, with actions and responses compliant with the ones that the operators could encounter during the operation of the plant.
The software simulator:

- Generates the signals coming from the plant
- Is connected with the PLC system and exchanges the I/O signals foreseen for the operation of the plant
- Through the interface the user can change the value of signals, generated by simulator or by the PLC, in order to simulate faults, sensor failures, anomalies, etc.

The main advantages given by this tool are:

- The operating personnel is trained using the interface of the supervision system that will be installed in the control room of the plant
- The operating personnel is trained on how to use the different pages of the automation system, also in case of plant anomalies

RHF CAMPAIGNS

Soon after the completion of the cold tests, in June 2003 the drying of RHF refractory was performed. All the steps regarding the firs pre-heating were completed successfully and in July 2003 the first phase of the production tests could be started.

Since the beginning the RHF was operated just using typical wastes of Piombino integrated plant, in particular BF dusts and steel plant dusts.
The partners agreed that it was not necessary to make a first phase using standard iron ore and coal blends. The trials carried out at CSM laboratory, in fact, fully proved the feasibility of the pre-reduction using the waste materials available inside Piombino works. The CSM trials had already defined some reference conditions that could be used in the demonstration plant (in terms of mix and of RHF operating conditions).

During the first operating period (July ÷ December 2003) some significant problems were encountered in different sections of the plant (details are reported at paragraph 2.3). Each solution was identified step by step during the trials and the relevant modifications to the equipment were carried out without shutting down the plant, during maintenance stoppages. This first operation phase made clear to the partners that the average time to carry out the necessary modifications to the plant was around one week – 10 days. This was due to the fact that even being a demonstration plant, all the equipment installed was of an "industrial" size and any modification, even if conceptually simple, took time.

After this phase it was also clear that in order to minimise any undesired stoppage during operation it was fundamental to have a constant technical plant assistance, to identify immediately the modifications necessary to the plant and to solve the problems possibly encountered during the operating phases.

During the next campaigns carried out between March and June 2004 the reliability of the plant was significantly increased, especially thanks to:

- The operational experience acquired in the previous months
- The modifications made to increase the stability of operation (plant modifications, changes to the operating practices and optimisation of the automation system).

The RHF campaigns performed in 2003 showed that the only critical point still open for the DRI production was related to the sticking behaviour of the wet green pellets, which tended to pack the RHF vibro-feeder after a short time of operation.
The final solution for this problem was identified and finalised: a dryer system for green pellets, which was installed in November 2004 between the pelletising disc and the RHF vibrating feeder.
The dryer has proved to be a key modification to the plant: in fact it strongly facilitates the continuous operation, solving the interruptions due to the packing of the vibro-feeder and allowing long periods of operation.
Beside that charging dried pellets into the RHF gives two other significant advantages: it substantially eliminates the decrepitation phenomena and it decreases the fuel consumption.

During the different campaign performed (test duration up to 16 hours per day) it was possible to investigate some important factors regarding:

- The mixing / pelletising process
  Operating procedures were defined in terms of:
  - Defining the mixes to be tested on the basis of an acceptable range for Fe/C ratio and according to the feasibility of the pelletising process
  - Definition and tuning of mixing and pelletising parameters to optimise the mechanical properties of the green pellets (quantity of binder to add, water added at the mixer and at the disc, rotating speed and slope of the pelletising disc, distribution of water spaying at the pelletising disc)
- DRI production
  Process parameters were defined in terms of different mixes charged into the RHF (different chemistry and size) and different operating conditions (temperature and residence time).
  These parameters were defined on the basis of the results obtained in terms of DRI metallisation, DRI chemistry (mainly carbon content) and DRI mechanical properties.

  On the basis of the results of this operation period for DRI production the following conclusions could be drawn:
  - The quality of DRI produced was satisfactory to be charged into the smelter (in terms of metallisation, carbon content and mechanical characteristics)
  - No sticking behaviour of DRI was observed
  - The content of undesired components in DRI (Zn, Pb, alkalis) confirmed the removal efficiency expected for the RHF process

The results obtained during the RHF operation as a single unit have defined the reference configuration for the joint operation with the smelter.

Thanks to the increased reliability of the plant reached in 2004, it was then possible to investigate some important factors regarding the process in different operating conditions (mainly quality of the charge, temperature and residence time).
The most significant campaigns have been selected (tests characterised by stable conditions and long periods of operation). On the basis of the data collected during the trial a detailed study has been carried out and some important conclusions could be drawn (the results of the study are reported in 2.3).

MAIN SUBJECTS INVESTIGATED DURING RHF CAMPAIGNS

During RHF campaigns, carried out between June 2003 and June 2004, short tests were performed with a duration varying between eight and sixteen hours.

The purpose of these tests was the tuning of some innovative plant components and the full characterisation of the process parameters. Here are the most important subjects investigated during this phase.

Mixing and Pelletising

The pelletising process is well understood since long time even if only empirical rules exist to optimise the balling disk operation as a function of the materials to handle and of the aimed green pellet properties. Therefore, various tests were carried out to optimise the quality of the green pellets for different input mix compositions.

In all cases, the precise dosing of raw materials and water is an important pre-condition to reach any quality target. To this purpose, some improvements were introduced in the control equipment and in the related control logics.

As a result of this work, the aimed process conditions are now steadily maintained and any effect of raw materials changes is quickly neutralised.

RHF feeder

Green pellets are distributed through the hearth by a special feeding device suitably developed. Tests have been performed to adjust the dynamic parameters of this device under different load conditions. As a general conclusion, the hearth load remains well distributed until material starts sticking and the resulting build-ups modify the material flow pattern.

To solve this problem, a number of design changes were tested, with limited success. The problem was radically removed only with the introduction of the green pellet dryer: in fact, dry pellets do not show any tendency to generate build-ups.

Hot DRI conveyor

This conveyor, designed and manufactured specifically for the project, is based on a metallic belt technology, which is widely adopted for the transportation of coal ashes and other high temperature materials. Some important modifications were introduced to limit the DRI temperature loss and to maintain a tight inert atmosphere. In summary, the performance of the conveyor has met all the expectations and only minor changes have been introduced to increase its reliability. In particular, the temperature drop between the RHF extraction screw and the metallic belt end- point has been found around 100 °C.

RHF process

The RHF burner system was designed with the help of two physical-mathematical models:

- A 1-D kinetic model, taking into account the main chemical reactions occurring in the pellet bed, such as Fe reduction, C gasification or combustion, Zn and Pb reduction and volatilisation, etc.
- A 3-D CFD model, simulating the chemical heat transfer processes occurring in the RHF gas phase. The 1-D model above represents the boundary condition for this 3-D model.

Details are reported at paragraph 2.6.4 and 2.6.5.

The data collected during the RHF test campaigns have been utilised to calibrate these two models, in order to improve their accuracy (2.3). Moreover, the test data have been analysed by statistical methods, in order to reduce the effect of measurement inaccuracies and correlate phenomena of difficult physical interpretation.

Different linear correlations have been found considering all or a subset of the following parameters:

RD^{DRI}	reduction degree of DRI
RD^{GP}	reduction degree of green pellets
C^{GP}	carbon content in green pellets
H_2O^{GP}	water content in green pellets
charge	charge distribution across the hearth
t_{res}	residence time

O_2^{OG}	oxygen content in off gas
T^{OG}	off gas temperature
T_1^{RHF}	temperature in the first zone of RHF
T_2^{RHF}	temperature in the second zone of RHF
T_3^{RHF}	temperature in the third zone of RHF

Some examples of the resulting correlations are shown in Figure 1.

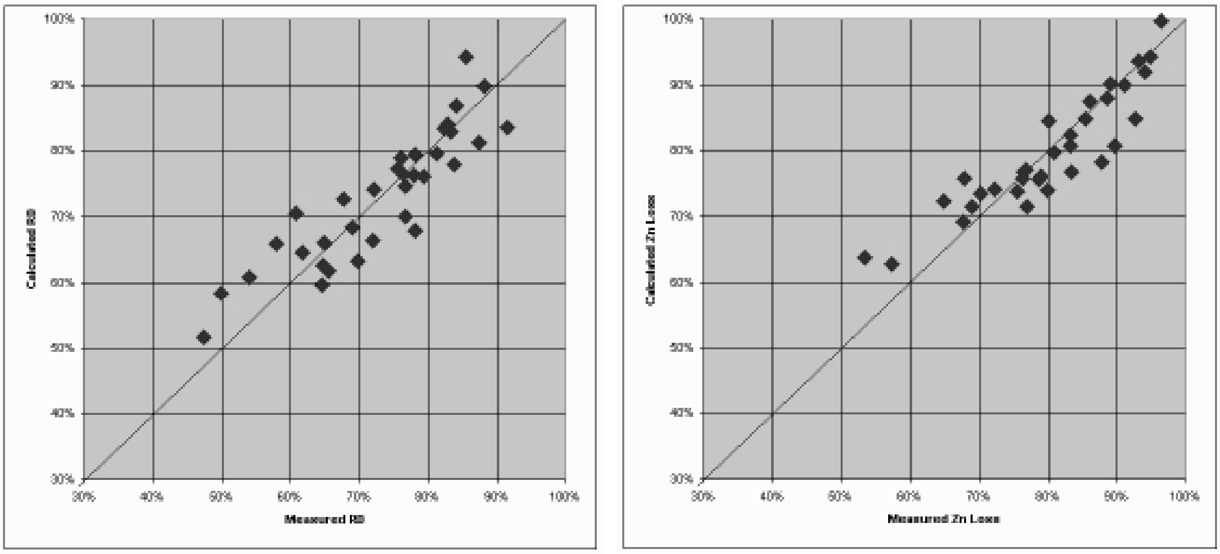


Figure 1. Reduction degree and zinc removal: calculated vs. measured

Off-gas conditioning system

The gas conditioning line consists of a refractory lined post-combustion duct, gas quencher with water sprays, air dilution station, and bag filter. Even if all these units belong to proven technologies, some tuning was necessary to avoid problems, mainly dealing with high moisture contents in the gas. In addition, due to combination of the RHF and the NST off-gases into a common suction system, some difficulty was found to balance the pressures of the two units, which was fixed by a small design change of the RHF offgas duct.

Currently, the gas system performs in full compliance with the design requirements.

SMELTER CAMPAIGNS

In December 2003 the first pre-heating of the smelter was carried out and an unexpected significant problem was encountered to the refractory. Due to this problem it was necessary to postpone the first smelting.

At this point the partners asked that the project be extended of six months beyond the original termination date (30-06-2004). The Commission granted the new completion date: 31-12-2004.

To analyse the causes of the damage suffered by the refractory, a stress thermal analysis of refractory bricks was performed using ANSYS (the study is reported at paragraph 2.6.3).

In the period between February and December 2004 the following campaigns were carried out for the smelter:

- Hot tests for the smelter unit, using pig iron and cold metallic charge (BF pellets, DRI) to set-up the smelting equipment and the relevant operating practices
- Plant operation of RHF + smelter (tests of short duration), to define the reference configuration of the plant and the reference operating conditions of the global process.

During the trials the following procedures were tested, evaluated and optimised: start-up and shutdown procedure, tapping procedures and safety operating practices.

MAIN SUBJECTS INVESTIGATED DURING SMELTER CAMPAIGNS

The experimental campaign for testing the smelter process can be subdivided in three main phases. Phase 1 (completed) was aimed at testing the most important plant components. Phase 2 (almost completed) is dedicated to investigate the characteristics of the process and to tune the operating practices. Phase 3 (under way) has the purpose to characterise the process and plant performances.

Phase 1

The main target of this phase was the checking of the plant components, in order to verify their compliance with the design criteria and their correct operation. This phase may now be considered completed and most of the relevant operating problems have been suitably fixed.
Here is a list of the main components and the related problems:

Refractory lining

As expected, the slag zone is the most critical area for the refractory lifetime. The slag self-protection according to the “freezeline” concept, which was the basis of the cooling system design, was shown to be valid only under steady state conditions. During start-ups and other transient periods, temperature and slag composition show big fluctuations, with a consequent quick erosion rate of the refractory lining. Picture 5 shows the erosion profile of the slag and metal zones after a smelting test.
To minimise the problem, the slag zone and the hearth have to be lined with a refractory material providing a strong resistance to chemical attack under both oxidising and reducing conditions.

DRI feeding chute

This device operates satisfactory without need for design changes.

Coal injection system

The regular performance of the pneumatic coal injection is a key pre-condition to carry out any smelter tests.
The commercial system installed at Piombino showed a number of problems:

- Difficult control of the coal dosing, with limited operability range;
- Frequent blockage of the line feeding;
- Wide fluctuation of the coal flowrate;
- Some clogging of the coal nozzle at the lance tip.

To overcome these problems several changes were introduced to the coal feeding and transportation system as well as to the design of the oxy-coal lances. As a result, the system performance has improved, even if this remains the main cause of unplanned delays during tests.

Copper cooling elements

The copper cooling plates represent the main barrier to the refractory erosion in the slag area. The design of these elements is intrinsically safe, since water is kept outside of the vessel shell. A very positive result is the observation of acceptable copper temperatures at the tip of the plate even with an almost completely bare plate and a very turbulent process environment.
Therefore, the original choices regarding the shape of the plates and their arrangement are fully confirmed.

Phase 2

This phase was aimed at investigating the characteristics of the process and tuning the operating practices. Most characteristics of the process have been verified and proven, but some of the points need further analysis and better operating practices and control systems need to be implemented.

Melting of cold raw materials, to prepare the initial liquid metal pool (“hot heel”)

A standard procedure has been set-up using the oxygen burner for reheating the vessel and first melting. After that, oxygen and coal injection starts and the furnace is charged regularly with buckets of pig iron and fluxes, until a liquid pool of sufficient volume is formed. This procedure is now fully consolidated and is systematically adopted on each test.

Keeping liquid bath in a stable state, by appropriate coal and oxygen injection

During standby periods, it is important to maintain the smelter on idle without undesired drifts of the process parameters, such as:

- Metal and slag temperature;
- FeO in slag and metal carburisation;
- Slag basicity (e.g. affected by the coal ashes);

These conditions must be maintained by injecting the necessary amount of coal and oxygen. The correct set-points depend also on the status of the refractory lining and on the consequent heat losses to be counter-balanced.

Stirring of the liquid bath

The stirring of the liquid bath, in order to transfer energy and material from the upper to the lower zone of the vessel, is a key mechanism in the process dynamics. The efficiency of this mechanism has been successfully observed in various tests while, in some cases, the stirring process does not activate properly due to any of the following reasons:

- The slag liquidus temperature is too high, with consequent freezing of the slag area around the lance tip.
- Coal flowrate fluctuates too widely, with consequent bad oxy-coal reaction
- Slag viscosity is too high, resulting in insufficient bath turbulence.

In all cases, the solution is the availability of an effective thermal and chemical slag control system. This is a critical point, still under consideration, since the response time of the existing system is not in line with this requirement.

Reduction and melting of cold Fe-bearing materials

After the start-up stage, the charging of cold iron-bearing materials was tested, to evaluate their smelting behaviour. The main considerations resulting from these tests are as follows:

- The smelting of pellets (either DRI or iron ore) in the bath is very quick, provided the slag properties, such as viscosity and liquidus temperature, are in the correct range.
- The charging of highly oxidised materials (BF pellets) results into an increased risk of slopping, due to massive CO generation.
- The reduction rate seems good, even if quantitative data couldn't be collected.

Coupling of RHF and NST smelter

The charging of hot DRI, produced by the RHF was one of the main targets of this phase. This mode of operation was tested only for short periods (hours) due to collateral problems, in particular with the coal injection, the gas suction and the tapping system.

The transfer of hot DRI from the RHF to the smelter was very smooth and, after fixing some minor mechanical problem, the switching between coupled and separate operation was easy to make. From these tests, the following considerations could be drawn:

- The smelting of hot DRI pellets was complete and very fast;
- Even if slag became more foamy, no slopping occurred;
- Post-combustion by the upper oxygen lances was activated only for short periods. It's effect on temperatures and gas composition seems fully in line with the theoretical expectations.

Efficiency and control of FeO in the slag and metal carburisation by oxy-coal injection

The execution of the smelting tests has allowed observing the dependence of the reduction parameters on the oxygen and coal rates. In particular, the following conclusions may be drawn:

- Under normal bath conditions, FeO in slag and metal carburisation are correlated each other very closely.
- The measurement of C in the metal is impossible during the whole start-up phase. Therefore, the slag FeO measurement (by O activity probe) was elected as key indication to control the process.
- The reduction potential of the injected carbon depends dramatically on the slag properties. With "bad" slag, reduction does not take place.

Again, the control of the slag and metal chemistry was recognised to be a key factor to reach and maintain the proper process conditions.

Casting and separation of hot metal and slag

The main purpose of the siphon system was to maintain a constant level of metal and slag in the vessel, with a continuous overflow of the liquid products. Main drawback is its relatively big thermal capacity in comparison with the limited hot metal and slag production rate. It is therefore difficult to maintain these products in the liquid state, mainly during start-ups and idle times. To solve this problem it was decided to simplify the tapping system and tap metal and slag on a batch basis.

The final drain of the smelter, at the end of a test campaign, is made through a bottom drain hole. Despite of the limited space available, the operation of this taphole has always been satisfactory.

Phase 3

Due to the non-conclusive results of the previous phase, *the partners decided to continue the test activity beyond the original deadline. Phase 3 test campaigns were terminated in February, 2006.*

Purpose of this phase was the analysis and the control of the main process parameters, as a function of the operating conditions, and precise identification of the plant performances:

- Efficiency of post-combustion
- Heat removal by the cooling system
- Coal injection yield (C losses in gas carry over and in slag)
- Coal and oxygen consumption rates
- Metal yields (Fe in gas carry over, metal inclusions in slag)
- Control of hot metal composition (C, Si, de-S and de-P, if any)
- Maximum productivity
- Other cost sensitive factors (relinings, maintenance, utilities etc.)

The results of the phase 3 are described in detail in the ANNEX H and allow to evaluate the performance of the process and give indications for the definition of the operating conditions and design of an industrial plant.

EMISSIONS MONITORING

Emissions have been measured during some significant periods of the tests campaigns (2.5).

The emissions values measured during the tests campaigns are very low (even lower than expected).

Other measurement campaigns are foreseen during the tests of long duration, with both units in operation, to verify and confirm the values that until now have been registered.

1.4 Conclusions

The experimental set-up of an innovative process needs a massive investment in financial and human resources. Even if a great deal of development work has already been done, the partners are aware that much has still to be done before this process may be considered ready for the industrial exploitation of the smelting section.

The tests of long duration (7 days) carried out to complete the research programme, one in October, 2005 and one in February, 2006, *have given significant results regarding the process operating conditions, consumption and productivity*.

The demonstration phase has confirmed the preliminary expectations of the production cost; the next development step should be a commercial demonstration unit with annual capacity around 200,000 tons.

The two main aspects to face during the further development stage are:

- Selection of a refractory lining and a cooling system able to reduce the refractory consumption to reasonable low value

- Handling of liquid metal and slag, in order to obtain a sufficient separation of the two phases

However, although the new smelting technology in its current stage is not completely proved, *the good results already achieved make the partner optimistic about the future results and the successful completion of the development stage*

1.5 Exploitation and impact of the research results

After the first phase of the development of the new technology, the partners still believe that the possible applications for the new process are the same that were originally indicated among the objectives of the project:

- To convert iron-bearing by-products into valuable metals (hot metal production according to the amount of wastes treated)
- To produce hot metal at low-mid scale size (typically around 500,000 tpy), in order to match with modern mini-mill architectures (hot metal used as valuable scrap substitute)

Even if the new technology is not ready yet for the industrial exploitation, it is believed that the results obtained during the tests of short duration have substantially proved the technical feasibility of the process. Instead, what has not been completely proved is the economic feasibility of the technology.

As regards the investment cost the economic feasibility has been mostly proved: the preliminary estimation made at the beginning of the project, in fact, was confirmed.

The tests of long duration, carried out in 2005 and 2006, have given significant results regarding the process consumptions (coal, oxygen and also minor utilities).

The solution selected for the refractory lining must be improved and further on tested, even if very useful indications have been withdrawn from the long duration tests; the actual refractory consumption may be verified only after some months of operation (some days are not sufficient).

Publications resulting from the project

1. Stahl und Eisen 124 (2004) Nr. 1, pp. 33/38
   "New Redsmelt NST process improves environmental impact on iron and steelmaking"
   A. Guglielmini, L. Chiappelli, P. Fontana, P. Bertossi, R. Degel
2. Stahl und Eisen 125 (2005) Nr. 5 (still to be published)
   "The Redsmelt NST plant at Piombino: first results and future outlook"
   L. Chiappelli, A. Guglielmini, P. Bertossi, G. De Marchi, P. Fontana

Conference presentations resulting from the project

1. METEC 2003, June 2003, Düsseldorf
   "Redsmelt NST: an innovative technology for the improvement of the environmental impact of iron and steelmaking"
   G. Gosio, L. Chiappelli, R. Degel, P. Fontana, P. Bertossi
2. STAHL 2004, November 2004, Düsseldorf
   "The Redsmelt NST plant at Piombino: first results and future outlook"
   A. Guglielmini, L. Chiappelli, P. Bertossi, R. Calcagno, G. De Marchi

Patent applications deposited

One patent application resulting from the project has been deposited in different countries:

"Metallurgical reactor for the production of cast iron"

The reference data of such patent application are the following:

COUNTRY	FILING DATE	APPLICATION N°
ITALY	14-05-2003	GE2003A000033
EUROPE	29-04-2004	04010160.2
CANADA	05-05-2004	2,466,398
AUSTRALIA	06-05-2004	2004201935
SOUTH AFRICA	07-05-2004	2004/3505
INDIA	11-05-2004	Not available
USA	13-05-2004	10/844,362
CHINA	13-05-2004	200410043129.7
BRAZIL	14-05-2004	0401753

In the following the abstract of the invention and the relevant reference figure are reported.

Abstract

Metallurgical reactor for the production of cast iron, consisting of a metal casing (1) internally lined, at least partially, with refractory material (R) and provided, in the region of the top closure, with a duct (9) through which high-temperature ferrous material is introduced, said reactor being equipped with a first series of lances (13) for injecting the comburent gas, which are suitably directed and arranged on at least a first bottom level situated in the vicinity of the crucible (101) for collecting the cast iron (2) and through which, in association with a comburent gas, coal of suitable grain size is blown by means of a suitable carrier gas. Said duct (9) has suitable cooling means and is provided, in the bottom terminal part, with nozzles for blowing in compressed gas. The middle zone (201) of the casing (1) of the reactor is lined internally with refractory material, pockets for receiving plates (11) made of metal which is a good heat conductor being formed in said lining (501), said plates (11) being provided on their side directed towards the outside of the reactor with heat exchanger means for cooling thereof.

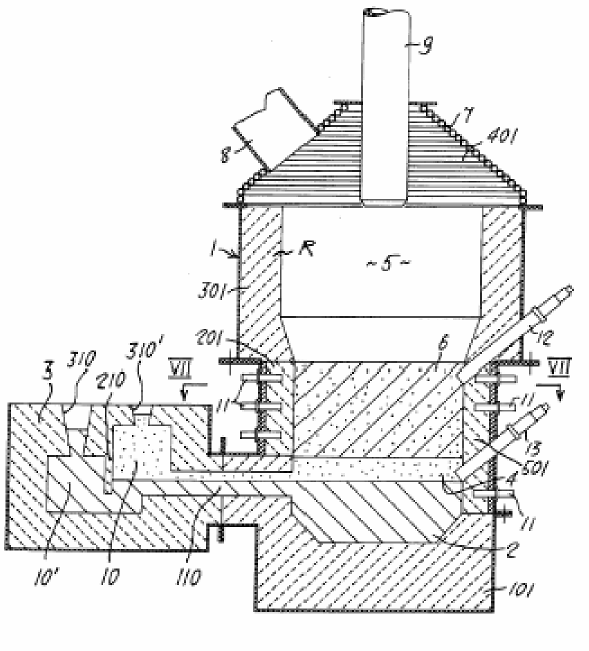


Figure 2. Patent application – Reference figure

2 Technical description of the results

2.1 Description of the plant

Figure 3 shows the basic concept of the process and Figure 4 shows the original plant arrangement in Piombino, before the installation of the dryer for the green pellets.

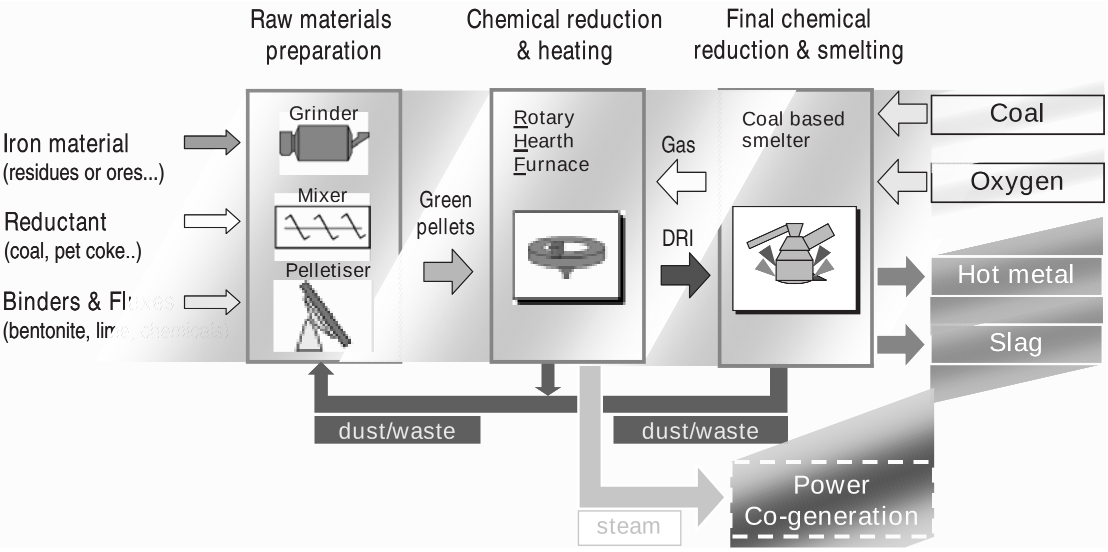


Figure 3. Process concept

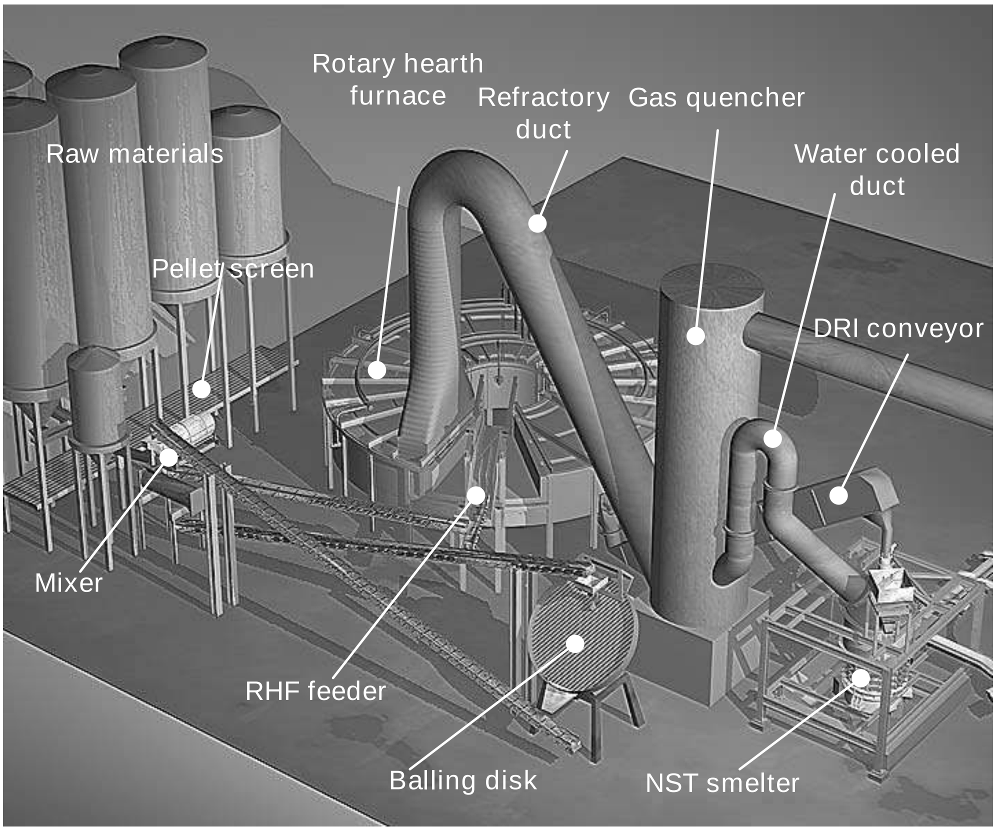


Figure 4. 3D view of the demo plant in Piombino

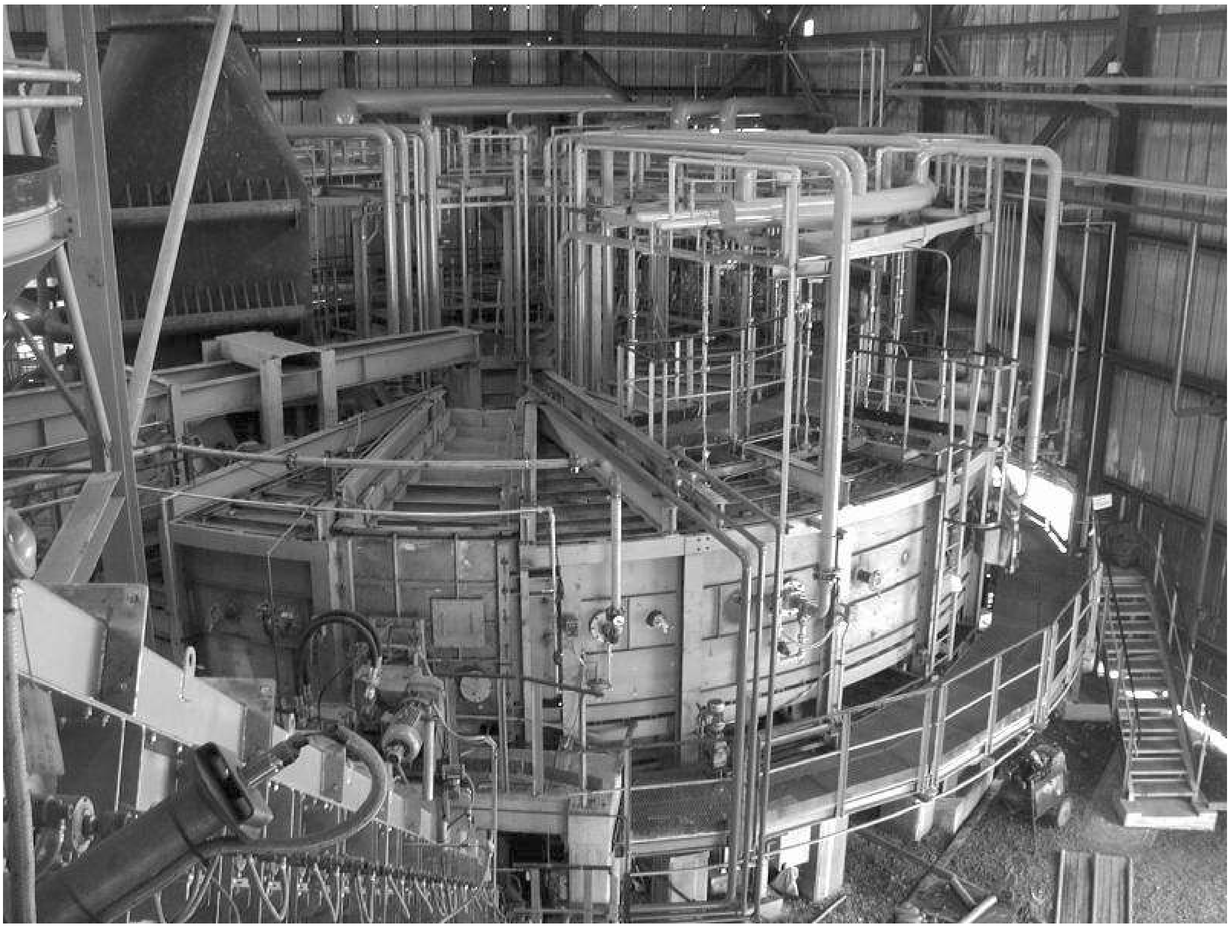
Materials preparation

Green pellets are prepared from finely ground iron-bearing materials and a carbon-based reductant, such as coal, coke or pet-coke. (In the specific case of Piombino the green pellets are prepared from waste materials, BOF and BF dusts; it is not necessary to add any separate coal, due to the high carbon content in BF dusts. For the demonstration campaigns it was necessary to choose materials, which were "naturally" suitable for pellettisation, i.e. sufficiently dry and with the right granulometry. The demo plant, in fact, could not be equipped with a drying-grinding section).

A wet blend is then prepared in a mixer, where the raw materials are carefully dosed with the addition of water and of small quantities of binder (typically bentonite). The resulting mixture is pelletised on a rotating disk, adding some water. Green pellets are then screened to remove the under- and over-size fractions that are recycled, while the sized product is conveyed to the dryer and then to the charging device of the RHF.

Rotary Hearth Furnace

Picture 2 shows the Rotary Hearth Furnace built in Piombino plant.



Picture 2 The RHF in Piombino plant

Green pellets are charged into the RHF and distributed into a uniform layer of about 20 mm across the whole width of the hearth.

The rotating annular hearth is placed in a furnace chamber covered by a suspended-type roof. The furnace side walls, the roof and the hearth are refractory lined to allow an operating temperature up to 1450 °C.

In each firing zone fuel and air flowrates are individually controlled by the control system, in order to obtain the desired temperature and gas composition (CO and O_2).

After charging, pellets are quickly heated up to the reduction temperature. Their total residence time on the furnace hearth to reach a final metallisation degree of 70-90% is between 10 and 18 minutes. Depending on the different raw materials properties, the DRI specific production ranges between 60 and 100 kg/m^{2}h.

The heat necessary to the process is provided by four different energy sources:

- Combustion of the auxiliary fuel (CO-rich gas from the NST converter in an industrial plant, natural gas in the demonstration plant in Piombino)
- Combustion of the CO resulting from iron oxide reduction
- Combustion of volatiles released by the reductant (coal)
- Combustion of a fraction of the reductant itself (carbon burnout)

The utilization of these energy sources is clearly in competition with the undesired phenomenon of the iron re-oxidation. The design of the demonstration Rotary Hearth Furnace for this project has been specifically aimed at optimising this complex gas-dynamic system. It includes special burners and "air wickets", for the injection of secondary combustion air, capable to adjust the proper degree of turbulence in each zone and at each level of the furnace chamber. Another critical factor to be duly considered in the RHF design was the need for an extremely accurate temperature control over the whole area of the hearth in order to obtain consistent mechanical and chemical properties of the produced pellets. The burner system has been designed to meet all these targets and to guarantee the minimum NO_X formation.

The DRI pellets so produced are then discharged via a water-cooled screw into a chute and then transferred to the NST smelter by a continuous metallic conveyor (designed for hot DRI transportation) heat resistant and enclosed in a gas-tight shaft.

Part of the waste gas energy of the RHF is used to dry the green pellets. In an industrial plant the waste gas energy would be also used to preheat the combustion air and to provide heat for raw materials drying. In large-scale plants the waste gas energy would also be used to produce steam by a waste heat boiler.

Table 1 shows the main data of the demonstration RHF plant in Piombino.

Data		
DRI production	t/h	4 ÷ 6
Wall-to-wall diameter	m	13
Hearth width (active)	m	3.5
Useful hearth surface	m^2	75
Inner height	m	1.1
Rotation speed	rph	0 ÷ 6
Hearth wheels	-	Fixed
Hearth driving groups	-	3
Control zones	-	3
Fuel gas	-	natural gas
Fuel gas consumption	GJ/t_{DRI}	5.6
Combustion air temp.	°C	20
Max furnace operation temp.	°C	1450
Burners	-	13
Fuel gas wickets	-	32
Air wickets	-	16
Electric energy cons.	kWh/t_{DRI}	100

Table 1. RHF plant: main data

NST Smelting Furnace

Figure 5 shows the original arrangement of the smelter built in Piombino (equipped with the tapping siphon).

The NST furnace is a non-tilting vertical vessel. Hot DRI is charged by gravity from the top by a water-cooled chute, placed in the centre of the vessel. An air curtain around the lance tip minimises carry over of DRI directly with the waste gas stream.

The smelting reactor is equipped with two levels of side lances (three lances per level). The position and the orientation of these lances is aimed at generating the proper chemical and fluid-dynamic conditions for the process The upper lances inject oxygen into the emulsion level to promote post-combustion in the transition zone; the lower lances inject oxygen and coal into the hot metal bath. With this arrangement the gas injection promotes a slag turbulence that should be sufficient to convey the necessary heat energy from the exothermic (post-combustion) zone to the endothermic (smelting) zone where the FeO direct reduction takes place. Relatively coarse coal is utilised to reduce the carbon losses and improve the hot metal carburisation.

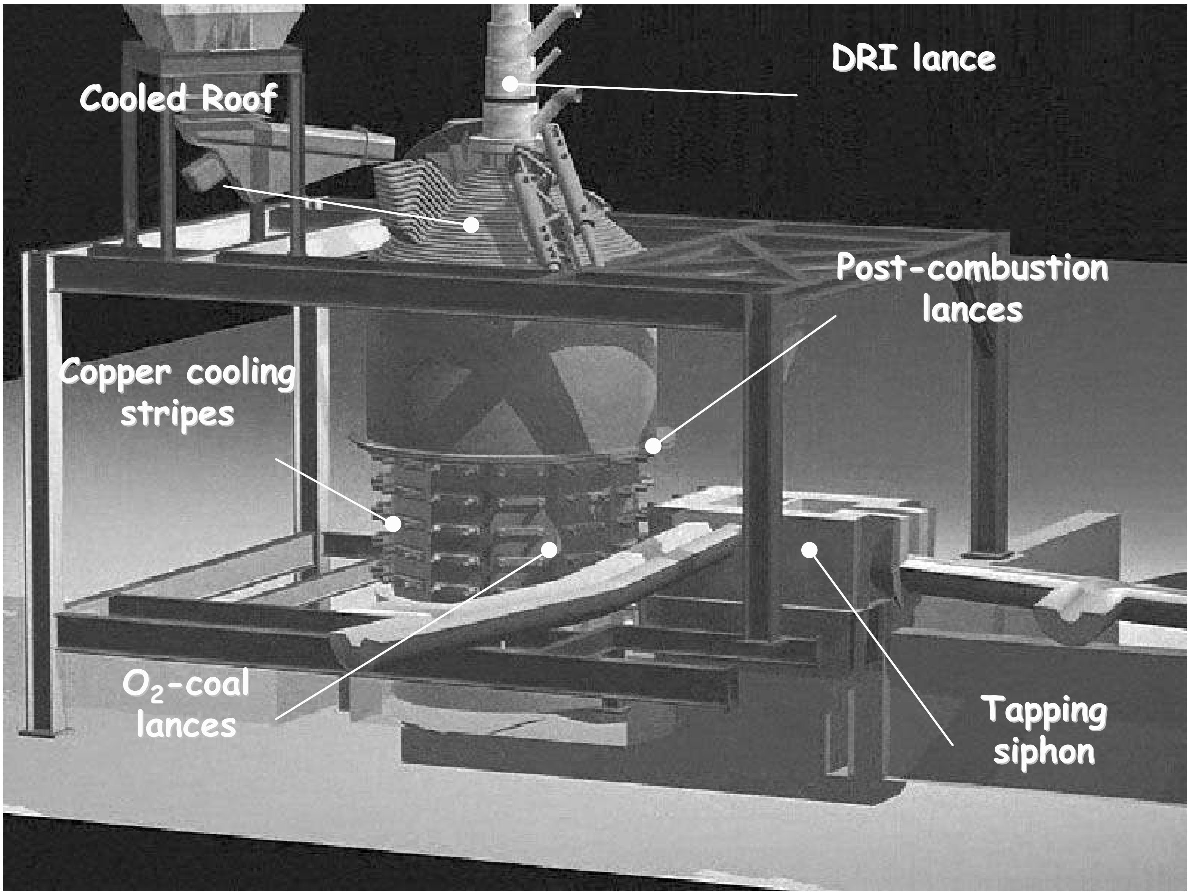


Figure 5. SMELTER – 3D view of general arrangement

The smelter has been designed for the target production of 3 tons of hot metal per hour, considering a low conservative value for the productivity: 1.8 t/(h m^2).
Aim of the next tests of long duration is to prove that there is a sufficient energy transfer into the bath: this is a necessary condition to reach at least the target production. Theoretically a higher productivity should be confirmed.

For the more critical area of the vessel (slag and metal-slag interface) six cooling systems were initially taken under consideration:

1. Air-cooled vessel
2. Water-spray cooled vessel with steel shell
3. Water-spray cooled vessel with copper shell

4. Copper staves placed behind the vessel lining
5. Vertically placed copper elements in between the sidewall lining
6. Horizontally places copper stripe system in between the sidewall lining

A thorough comparison of all systems showed that the horizontal stripe system allows the most flexible operation, minimising refractory wear in the slag zone at acceptable investment costs. For safety reasons water channels of the cooling elements are placed outside the shell.

Additional CFD-calculation supported the detailed dimensioning and fine-tuning of the cooling concept. Stripes with the dimension of 200/60/250mm and a distance of 220mm showed good results regarding the cooling effect. Thermocouples are placed in the sidewall and in the copper elements, which gives additional indication of the lining condition during operation.

For the top of the smelter a water-cooled roof has been chosen, to avoid refractory wear due to the high temperatures resulting from post combustion. After that a water-cooled duct collects and cools the smelter off-gas to the proper temperature for entering the quenching system. In the demo unit, for keeping the capital cost as low as possible, the smelter off-gas is not utilized as RHF fuel, but is completely burned. In future commercial units, this gas would be cooled and cleaned without combustion, sent to a small gas-holder to stabilize its pressure and then utilized in the RHF as burner fuel.

The bottom part (hearth) was originally equipped with a siphon taphole similar to those adopted in cupola or mini-blast furnaces (slag and hot metal separated with a skimmer).

The choice of the siphon was motivated by two main reasons:

- The siphon allows a continuous overflow of the liquid products
- Siphon tapping maintains a constant bath level of metal and slag in the vessel. This eliminates the level fluctuation of slag/hot metal, minimising also the refractory wear

Main drawback of this system is its relatively big thermal capacity in comparison with the limited hot metal and slag production rate. During operation it was difficult to maintain the products in the liquid state and it was often necessary to stop the hot DRI charging, because it was not possible to evacuate the slag, which froze in the refractory block between the vessel and the siphon.

To solve this problem it was decided to simplify the tapping system and tap metal and slag on a batch basis.

At the end of each campaign the vessel is completely drained via an emergency tap hole at the bottom of the smelter. Despite of the limited space available, the operation of this taphole has always been satisfactory

Table 2 shows the main data of the NST smelter in Piombino.

Plant data			Process data (target)		
Inner hearth diameter	m	1.44	Hot metal production	t/h	3
Inner diameter in gas zone	m	1.7	Post-combustion ratio	%	30
Internal height	m	4.5	Coal rate	kg/t$_{HM}$	260
Copper cooling elements	-	55	Oxygen rate	Nm^3/t$_{HM}$	325
Freeboard side cooling	-	no	Fluxes (burnt lime/dolom.)	kg/t$_{HM}$	60
Freeboard roof	-	water pipes	Slag CaO/SiO$_2$	-	1.2
Furnace pressure	-	atmospheric	Hot metal Carbon	%	3÷4
Start-up burner	-	oxy-gas	Hot Metal Sulphur	%	0.1
Charging and blowing	-	continuous			
Oxy-coal lances	-	3			
Oxygen PC lances	-	3			
Hot metal tapping	-	siphon (now modified)			

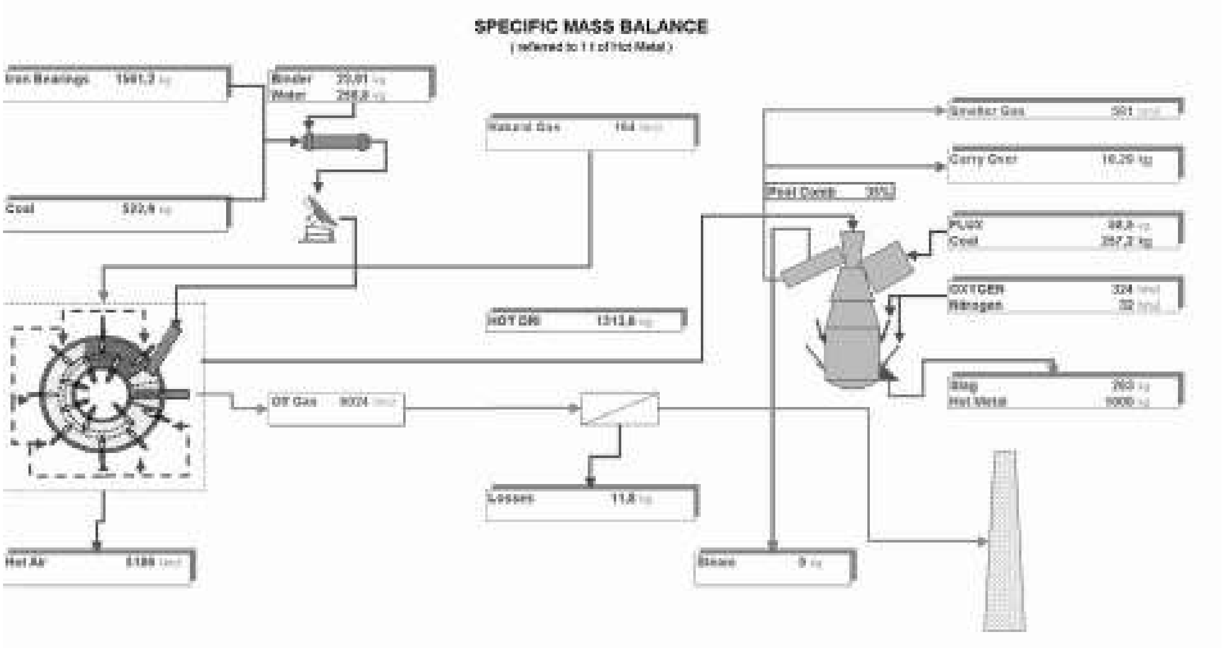
Table 2. NST smelter: main data

In stable conditions it is expected that the slag and the hot metal should be comparable with the ones produced by the blast furnace, with two main differences:

- The hot metal will be lower in carbon: it should contain approximately 3-4 % carbon
- The slag will contain a higher FeO that in any case should be kept lower than 2-3 %, to avoid a too quick erosion of the refractory.

Figure 6 shows a preliminary material and energy balance for the complete process under typical conditions of the demo plant in Piombino.

Figure 6. Typical material and energy balance



Off-gas system

Off gas leaving the Rotary Hearth Furnace at a temperature around 1100 °C and not completely oxidised is conveyed to a refractory lined duct. Suitable nozzles for fresh air injection are located after the off-gas entrance in the refractory lined duct in order to burn compounds like CO, and to limit the temperature below the value at which flying ashes start to melt. A free oxygen level greater than 3%, high turbulence degree and a residence time above 1 second are suitable conditions to reach the complete combustion of the off-gas; the air injection nozzles are distributed homogeneously along the duct in order to minimise the NO_x formation.

If compared with the off-gas leaving the RHF, the off gas coming from the smelter has a higher temperature (about 1700 °C) and a lower post-combustion degree with consequent unburned compound content (CO+H2 is more than 30%).

Smelter off-gas is conveyed to a water cooled duct, where the post-combustion air flowrate is injected. The combustion parameters (residence time, oxygen, turbulence and temperature) are the same used for RHF off-gas treatment.

The RHF and smelter gas at a temperature not higher than 950°C are then conveyed to the same quencher, to reduce the fume temperature to about 320°. The "spill-back" type nozzles allow the complete nebulisation of water droplets and a fast gas temperature reduction.

An emergency stack equipped with a bleeder valve (self-opening on emergency) is placed at the top of the quencher.

The RHF primary, the smelter primary and the secondary dedusting air are finally sent to the dedusting plant.

The green pellets drying system

The RHF campaigns performed in 2003 showed that the only critical point still open for the DRI production was related to the sticking behaviour of the wet green pellets, which tended to pack the RHF vibro-feeder after a short time of operation.

The final solution for this problem was identified and finalised: a dryer system for green pellets, which was installed in November 2004 between the pelletising disc and the RHF vibrating feeder.

The dryer has proved to be a key modification to the plant: in fact it strongly facilitates the continuous operation, solving the interruptions due to the packing of the vibro-feeder and allowing long periods of operation.

Beside that charging dried pellets into the RHF gives two other significant advantages: it substantially eliminates the decrepitation phenomena and it decreases the fuel consumption.

The main design data of the dryer are the following:

- Green pellets input flowrate: 7÷10 t/h (wet)
- Bulk density of pellets: around 1.5 t/m^3
- Green pellets start moisture: 12÷14%
- Green pellets inlet temperature: about 50°C (due to some heat released by the lime hydration and to the high temperature of BF dust)
- Green pellets size: 8÷12 mm
- Green pellets final moisture < 2%
- Inlet Gas temperature: 250 °C
- Outlet fumes temperature: 150 °C
- Height of the pellets layer inside the dryer: 100÷200 mm
- Residence time inside the dryer: 8÷16 minutes

The drying of the green pellets has been designed optimising the energy consumption of the overall process. The drying, in fact, is made using the waste hot gas produced in the rotary hearth furnace (at a temperature around 800 °C), which is mixed and diluted with the fumes coming from the dryer itself, to reach the required inlet temperature of 250 °C.

Figure 7 represents the configuration of the new drying system (the coloured part highlights the new system installed in the existing plant).

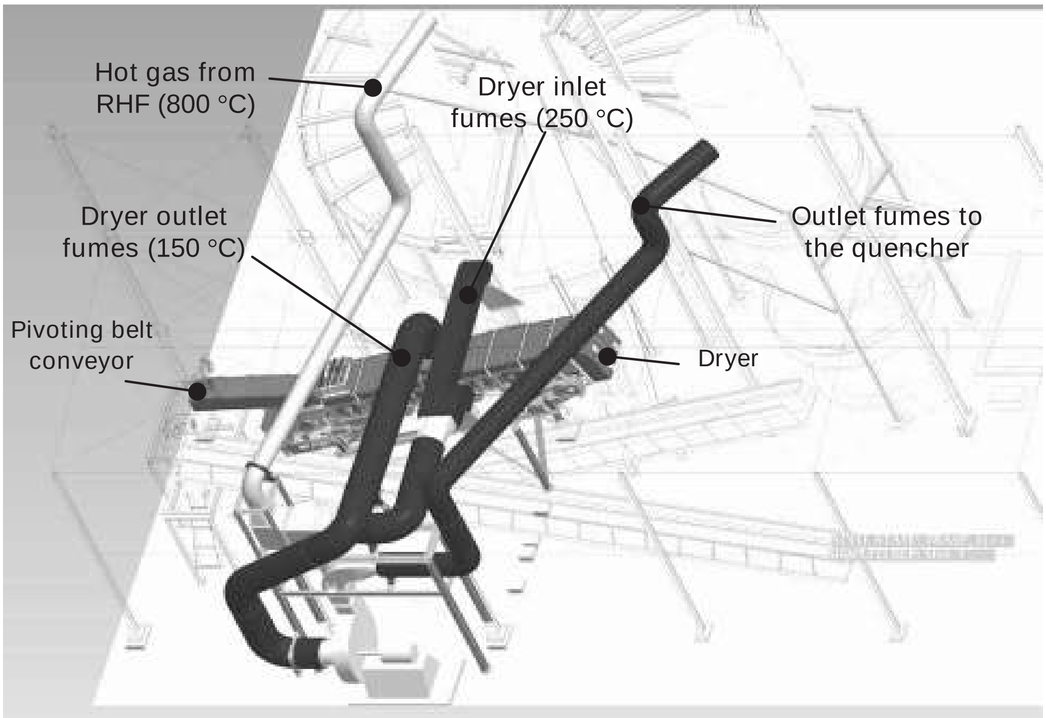


Figure 7. The new green pellets drying system – 3D top view

2.2 Laboratory tests

These trials were carried out in a batch test furnace at the CSM laboratory in Dalmine (BG – Italy) and were dedicated to characterise different blends of materials with different RHF operating conditions (mainly temperature and residence time).
Technological and chemical characterisation was made both for raw materials and green pellets charged to the pilot furnace.
The trials led to the production of different qualities of DRI, which were evaluated on the basis of technological and chemical characterisation tests.

Objective of this activity was to identify the blends and the furnace operating conditions that could be implemented during the operation of the demonstration plant, to reach the required product specifications regarding Fe metallisation, C content, mechanical strength, residual Zn, etc.

This activity was developed in cooperation with CSM, in the frame of the relevant sub-contract with LUCCHINI.

The laboratory tests were performed using the following waste materials coming from Piombino integrated steel works:

- blast furnace sludge (wet sludge, humidity around 23%)
- blast furnace dust (wet dust, humidity around 10% ÷ 15%)
- blast furnace dry dust
- steel plant primary dust
- mill scales

<u>TESTS PROCEDURE</u>

<u>Raw materials characterisation</u>

All the identified raw materials were fully characterized in terms of:

- <u>Granulometrical distribution</u>
  The pelletisation process for this specific application requires materials with granulometry as close as possible to the optimum: 80% below 100 μm and 100% below 250 μm.
  The granulometry tests are necessary to determine whether raw materials must be subject to a grinding process or if they can be charged directly to the mixing / pelletising section.
  The granulometry tests showed that these raw materials (except mill scales) do not need any grinding and can be directly processed by the mixing / pelletising phase.
- <u>Chemical analysis and humidity</u>
  Chemical characterisation of raw materials is necessary to decide the recipes that can be used for the reduction tests.
- <u>Grinding</u>
  The grinding tests are necessary to determine the grindability of the different raw materials. For this purpose two laboratory units are used:
  - a BOND ball mill (used for the production of fine material that is then processed in the pelletising disc)
  - a bar mill (mainly used to characterise different materials, comparing the results with BOND grinding)

  For each material the grinding tests are performed in both mills, with different residence times, to determine the optimum unit (ball or bar mill) and the optimum process parameters (residence time and mill speed).

- Mixing and Pelletising

  This is a very important step of the preparation process. The raw materials are charged into a mixer and water is added to reach the right blend humidity. After that the mix is charged into the pelletising disc and green pellets are produced.
- Green pellets characterisation

  A good mechanical quality of green pellets is an essential parameter for the industrial use, to resist the handling and the charging into the RHF.

  After pelletising the following characterisation is carried out:
  - Compression test
  - Bulk density
  - Drop test

Direct reduction tests

These tests were necessary to characterise different mixes in different operating conditions.

The tests were performed with residence times varying between 3 and 6 minutes in the first zone, and between 9 and 14 minutes in the second zone of the pilot furnace.

The laboratory furnace is mainly made of the following parts:

- First chamber, zone I, with oxidising atmosphere and temperatures between 700°C and 1100°C (for removal of water and volatiles and for pellet preheating)
- Second chamber, zone II, with under-stoichiometric atmosphere and temperatures between 1200°C and 1400°C (for the reduction process)
- Mobile hearth, capable of travelling between zone I and II and to the discharge zone
- Four analysis points to measure atmosphere composition
- Five thermocouples (two for each zone and one in the hearth)
- Two gas analysers for O_2 and CO
- A data logger for acquisition and recording

The parameters that may change for each mix charged into the reduction furnace are:

- Chemical composition of green pellets (Fe / C ratio, binder)
- Size of green pellets charged into the furnace (10 – 19 mm)
- Specific hearth load (kg pellet / m^2)
- Temperatures in the two zones of the furnace
- Residence time in the two zones of the furnace
- Composition of atmosphere in zone I and zone II

At the end of each reduction test a complete DRI characterisation is carried out, the DRI is cooled in nitrogen atmosphere (to avoid reoxidation) and is then characterised:

- Chemical characterisation: metallisation degree, total Fe, FeO, C and S, Zn, Pb, alkalis, etc.
- Mechanical characterisation: compression test and tumbler test according to ISO 3271. The unit used for the tumbler test (and the relevant operating practices) has been adapted, to take into account the product under testing.

TESTS PERFORMED

Before starting the reduction tests with the different materials coming from Piombino plant, some preliminary investigations regarding the effect of binders were made. In this case the raw materials used were pellet fines and anthracite.

- Aim: to reach good mechanical properties.

  In order to evaluate the effects of binders, different materials were used (bentonite, lime, silica, glass). The behaviour of different binders was investigated through the characterisation of DRI: granulometry, compression test and tumbler test.

  The best results were obtained using bentonite and silica.
- Aim: to reduce decrepitation phenomenon.

  Tests were performed to investigate the effect of charging temperature on decrepitation phenomenon (bentonite was used as a binder).

Results showed that the use of bentonite improves the resistance to decrepitation, allowing higher charging temperature.

After this preliminary study, different reduction tests were performed. The tests can be grouped in the following six steps:

Step 1 - Trial 1 ÷ 16
For these trials the following raw materials were used:

- Blast furnace dust (from 90% to 40% in the mix)
- Steel plant primary dust (from 10% to 60% in the mix)
- Binder (bentonite), around 1%
- No reductant needed (enough carbon is contained in blast furnace dust)

The materials were pelletised without grinding and the results were satisfactory.
In all the tests the DRI metallisation was fully satisfactory: higher than 85%.
The main results of these trials are summarized in the following table:

BF dust [%]	Primary dust [%]	Green pellets Dry / Wet	Decrepitation Yes / No	DRI Mechanical resistance Low / Medium / High
90	10	Wet	No	Low (1)
80	20	Wet	No	Low (1)
70	30	Wet	No	Low (1)
60	40	Wet	Yes (2)	N.A.
50	50	Wet	Yes (2)	N.A.
50	50	Dry	No	High
40	60	Wet	Yes (2)	N.A.
40	60	Dry	No	High

(1) The low mechanical resistance is due to the high level of carbon in DRI. The mechanical resistance improves by decreasing the BF dust percentage.

(2) The decrepitation occurs even if the temperature in the first zone of the furnace is kept low. This phenomenon is related to the very fine size of primary dust particles (more than 90% < 100 micron), which retain water.

Special tests were performed to investigate the effect of primary dust percentage on decrepitation phenomenon. Results confirmed that the resistance to decrepitation improves by decreasing the primary dust in the mix.
Further tests showed that the percentage of primary dust is not a limiting factor, when the green pellets are dried before entering the furnace.

Step 2 - Trial 17 ÷ 32
The BF dust used in step 1 had a very high level of carbon (around 37%), higher than the standard value of Piombino blast furnace. This anomalous value was probably related to the fact that the sample was taken soon after a stoppage of the blast furnace.
For this reason, in order to optimise the mechanical resistance of DRI, for step 2 another sample of BF dust was taken and used: a dry dust, with 26.5 % of carbon.
The tests were performed in the same reference conditions used for step 1 (same ratios between BF dust and primary dust, same operating conditions).
As expected, the mechanical resistance was good (two – three times higher than the values resulting from step 1).
Also the DRI metallisation was satisfactory.
The particles of the dry BF dust were finer than in the wet one and this took to an increase in decrepitation phenomena, even when primary dust percentage was between 10% and 30%. Further tests were performed and the results showed that a lower temperature in the first zone of the furnace was enough to avoid decrepitation, getting the same results obtained in step 1.
Some tests were performed charging dried green pellets and the satisfactory results of step 1, in terms of mechanical characteristics and decrepitation, were confirmed.

Step 3 - Trial 33 ÷ 42
In this step the mix was prepared with BF dust, primary dust and mill scales.
The utilization of mill scales took to a higher iron content in the green pellets and a consequent lower final carbon in DRI.
The DRI metallisation was good (> 80%), the decrepitation was negligible and, as expected, the mechanical characteristics were fully satisfactory.

Step 4 - Trial 43 ÷ 45
In this step the following mix was used: 50% BF sludge, 50% primary dust.
The tests were performed with dried green pellets.
The DRI metallisation was satisfactory and the mechanical characteristics were excellent (compression higher than 70 kg per pellet).

Step 5 - Trial 46 ÷ 49
In this step the mix was prepared with BF sludge, primary dust and BF dust.
The DRI metallisation was acceptable and no decrepitation was observed.
The mechanical characteristics were not satisfactory.

Step 6 - Trial 50
In this step the mix was prepared with BF sludge, primary dust and mills scales.
The results of step 3 were confirmed: the mill scales improve the mechanical resistance of DRI.

Test results took to the following main conclusions:

- The identified raw materials (except for mill scales) can be pelletised without intermediate grinding.
- The granulometry of raw materials is a fundamental factor to understand and avoid decrepitation.
- The final content of carbon in DRI is the limiting factor for the mechanical characteristics (the use of mill scales, material with high iron content, improves the mechanical resistance of DRI).
- No decrepitation is observed when the green pellets are dried before entering the furnace, with any composition of the mix. In this case the temperature in the first zone of the furnace can be kept much higher (up to 400°C higher), between 700°C and 1100°C. As a consequence the mechanical resistance improves.

This phase of laboratory tests identified the mixes that could be charged into the RHF and the process parameters to achieve high metallisation and/or high mechanical quality. The tuning of the process was made mainly acting on temperature and residence time.
The identification of the reference conditions for the demonstration plant was done aiming at the following objectives:

- No intermediate grinding needed (the demonstration plant is not equipped with a grinding unit)
- No decrepitation
- Good mechanical resistance
- Good metallisation

The results obtained during trials proved that the DRI so produced is suitable to be charged into the smelter. It must also be noted that the mechanical quality of DRI is a less limiting factor, when the DRI is directly charged into the smelter, as it happens in the plant of Piombino. In this case, in fact, the DRI is not subject to any handling, it is simply transported by a metallic conveyor and even if the mechanical resistance of the DRI is not high, a very small amount of dust is produced.

2.3 RHF campaigns – Analysis of results

2.3.1 Summary

Soon after the completion of the cold tests, in June 2003 the drying of RHF refractory was performed. All the steps regarding the firs pre-heating were completed successfully and in July 2003 the first phase of the production tests could be started.

The RHF campaigns can be sub-divided as follows:

- July ÷ August 2003: RHF hot tests
  The RHF hot tests were mainly devoted to test all the equipment included in the DRI production route, between raw materials bins and hot DRI discharging system.
- September ÷ December 2003: completion of RHF hot tests and first phase of tests of short duration
  The tests of short duration were devoted to investigate RHF operation.
- March ÷ June 2004: second phase of tests of short duration
  The main objectives of the second phase were:
  - to increase the stability of operation
  - to verify and optimise the quality of the produced DRI in different operating conditions (mainly quality of the charge, temperature and residence time).
- July ÷ October 2004 (August excluded): tests of short duration in connection with the smelter
- December 2004: tuning of the new drying system for the green pellets and last campaign in connection with the smelter

Since the beginning the RHF was operated just using typical wastes of Piombino integrated plant, in particular BF dusts and steel plant dusts.
The partners agreed that it was not necessary to make a first phase using standard iron ore and coal blends. The trials carried out at CSM laboratory, in fact, fully proved the feasibility of the pre-reduction using the waste materials available inside Piombino works. The CSM trials had already defined some reference conditions that could be used in the demonstration plant (in terms of mix and of RHF operating conditions).

During the first operating period (July ÷ December 2003) some significant problems were encountered in different sections of the plant. Each solution was identified step by step during the trials and the relevant modifications to the equipment were carried out without shutting down the plant, during maintenance stoppages. This first operation phase made clear to the partners that the average time to carry out the necessary modifications to the plant was around one week – 10 days. This was due to the fact that even being a demonstration plant, all the equipment installed was of an “industrial” size and any modification, even if conceptually simple, took time.
After this phase it was also clear that in order to minimise any undesired stoppage during operation it was fundamental to have a constant technical plant assistance, to identify immediately the modifications necessary to the plant and to solve the problems possibly encountered during the operating phases.

In the following a brief summary of the main problems that were encountered and solved during RHF operation is reported:

1. Due to a very high abrasion caused by BF dusts, the ploughs of the mixer were completely deteriorated after just two weeks of short tests. After the inspection of the supplier it was jointly decided to install a special type of ploughs made of tungsten carbide (a material with a very high resistance to abrasion). The ploughs installed in June 2003 performed in a satisfactory way and they are still in operation.
2. The nitrogen fluidisation system originally foreseen for the bin of steel plant dust was not adequate for this specific material. Inside the bin the material formed bridges, which felt down unexpectedly when fluidisation was activated. Under these conditions the material flowed out of the bin in an uncontrolled way (it behaved more like a liquid than like a solid).
   A new system was installed, based both on vibrations and on fluidisation. This new system, called vibra-flow, worked continuously, with an intermittence frequency that was adjusted according to

the behaviour of the material. Unfortunately also this system was not always effective: in some conditions the material still flowed out of the bin in an uncontrolled way, changing significantly the recipe set by the operators.
The problem was definitely solved charging the steel plant dusts into a bin equipped with a rotary star valve: the reached performance was satisfying, also during tests of longer duration (up to 16 hours).

3. The hoppers and chutes that discharge the mix into the pelletising disc and the green pellets into the rotary drum screen were inadequate to ensure mass flow. The wet mixture fed to the disc and the wet green pellets fed to the rotary drum screen have very high sticking characteristics. Accumulations and clogging of these sticking materials developed very quickly and plant interruptions occurred, requiring manual tapping to promote flow.
   A similar problem was encountered also for the emergency discharging system of the green pellets (used quite heavily, especially in the start-up and in the shut-down phases of each test).
   New discharging systems were installed (wider passing sections and more vertical position, to facilitate flow). For the emergency system an "open" design was adopted, to facilitate possible manual intervention.
4. The efficiency of the brush used to keep the classification grade in the rotary drum screen was not adequate to the mass flow. Due to the sticking characteristics of the wet green pellets and of the residual wet dust fed to the rotary drum screen, the openings of the screen were packed after a short time of operation. The screening of the green pellets had no effect (also wet fines were charged to the RHF feeding system). The problem was solved installing a new counter-rotating brush: the efficiency of the new cleaning system was satisfying and also under severe conditions (very wet green pellets and high degree of re-circulation) the openings of the screen were not packed.
5. The RHF vibrating feeder packed after few hours of operation, even when the green pellets produced from the previous steps of the process were of good quality.
   The wet green pellets had in any case very high sticking characteristics and the surface of the feeder was packed after a short time of operation.
   At the beginning a very simple drying system was installed inside the rotary drum screen, in order to remove part of the humidity. This additional step helped to have longer time of operation, but did not solve the problem.
   The problem was definitely solved only after the installation of the drying system for the green pellets, which was installed between the pelletising disc and the RHF vibrating feeder. The dryer was installed in November 2004 and the new configuration of the plant was tested in December 2004.
   The dryer has proved to be a key modification to the plant: in fact it strongly facilitates the continuous operation, solving the interruptions due to the packing of the vibro-feeder and allowing long periods of operation. Beside that charging dried pellets into the RHF gives some other significant advantages: it substantially eliminates the decrepitation phenomena, decreases the fuel consumption and improves the final quality of DRI.

During the different campaign performed (test duration up to 16 hours per day) it was possible to investigate some important factors regarding:

The mixing / pelletising process

Operating practices were defined for the mixing / pelletising process in terms of:

- Different mixes, by varying the ratio between BF dusts and steel plant dusts
- Quantity of binder added to the mix
- Quantity of water added at the mixer
- Start-up procedure at the pelletising disc
- Rotating speed and slope of the pelletising disc
- Quantity of water added at the pelletising disc
- Distribution of water spaying at the pelletising disc

These operating practices were defined through different steps:

- Definition of the mixes to be tested on the basis of an acceptable range for Fe/C ratio and on the basis of the results previously obtained at CSM laboratory
- Final selection of the mixes to be tested according to the feasibility of the pelletising process (not all the mixes could in fact be pelletised successfully, due to the coarse size of the BF dust)
- Definition of mixing and pelletising parameters according to the feasibility of the pelletising process
- Tuning of mixing and pelletising parameters to optimise the mechanical properties of the green pellets

Particular attention was given to the pelletisation process. With the completion of 2003 campaigns, in fact, it was clear that a good operation of the pelletisation disc required stable conditions.
To get this goal the following modifications were carried out:

- The inclination of the pelletising disc was changed to optimise the size of the produced green pellets
- An inverter was installed on the pelletising disc, so that it was possible to change the rotation speed during operation, without stopping the process
- Two regulation valves were installed, to regulate the water given at the mixer and the water given at the disc. The automation system was modified, so that the operator had just to set the water percentage requested at the mixer and at the disc.

After these modifications the pelletising process reached satisfying stable operation. The characteristics of the green pellets could be varied quite easily, changing the humidity content and/or the rotation speed of the disc. The production of the green pellets was quite constant in terms of flowrate: this factor is very important for the behaviour of the RHF vibro-feeder and for the subsequent good distribution on the RHF hearth.

The DRI production

Process parameters were defined for DRI production in terms of:

- Different mixes charged into the RHF (different chemistry and size)
- Different operating conditions (temperature and residence time)

These parameters were defined on the basis of the results obtained in terms of:

- DRI metallisation
- DRI chemistry (mainly carbon content)
- DRI mechanical properties

The samples of DRI were taken at the discharge of the hot DRI transport system. This conveyor, which is itself an innovative solution, was designed with two main objectives:

- To keep the metallisation of DRI (by the application of a nitrogen atmosphere for inertisation)
- To keep the temperature of DRI above 800 °C (by the application of an insulating system)

Both objectives were reached satisfactorily.

On the basis of the results of this operation period for DRI production the following conclusions could be drawn:

- The quality of DRI produced was satisfactory to be charged into the smelter (in terms of metallisation, carbon content and mechanical characteristics)
- No sticking behaviour of DRI was observed
- The content of undesired components in DRI (Zn, Pb, alkalis) confirmed the removal efficiency expected for the RHF process

During the campaigns carried out between March and June 2004 the reliability of the plant was significantly increased, especially thanks to:

- the operational experience acquired in the previous months
- the modifications made to increase the stability of operation (plant modifications, changes to the operating practices and optimisation of the automation system).

Thanks to the increased reliability of the plant it was then possible to investigate some important factors regarding the process in different operating conditions (mainly quality of the charge, temperature and residence time).
The most significant campaigns have been selected (tests characterised by stable conditions and long periods of operation). On the basis of the data collected during the trial a detailed study has been carried out and some important conclusions could be drawn (the results of the study are reported in the following pages).
The results obtained during the RHF operation as a single unit have defined the reference configuration for the joint operation with the smelter.

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2.3.2 Analysis of results

RAW MATERIALS

All the tests have been performed using the following raw materials:

- Blast Furnace Dusts (indicated also like PAF)
- BOF Dust from dry-type electrostatic precipitator (indicated also like PAC)
- Iron dust (only in one series of tests) coming from a mixture of ground ore and re-oxidised iron fines

The carbon needed for reduction comes with BF dusts, and pelletising is performed using bentonite as binder.

Table 3 summarises the average physical and chemical properties of the raw materials.

	BOF DUST	IRON DUST	BF DUST	
	Average	Average	Average	Limits
Fe tot.	63.44	68.86	37.25	Min 33% max 44%
Fe met.	8.81	-	-	
FeO	28.18	-	16.76	
Fe2O3	46.88	-	-	
SiO2	1.84	0.42	5.63	
Al2O3	0.01	0.01	2.14	
Cao	5.21	0.01	3.45	
MgO	2.02	0.01	0.21	
TiO2	0.07	0.017	0.11	
Mn	1.92	0.08	0.63	
P	0.05	0.026	0.05	
Na2O	1.09	0.003	0.05	
K2O	0.35	0.011	0.44	
Zn	1.70	0.007	0.05	
Cr	0.04	0.037	0.04	
C tot.	0.70	0.01	32.18	Min 25% - max 40%
S	0.19	0.004	0.33	
Moisture w.b.	0.25	1.0	0.30	
Density kg / dm^3	0.8	0.75	1.34	

Table 3. Raw materials properties

In the last column the ranges of carbon and iron content of BF dust are reported. The BF size distribution is not the optimum for the reduction process, due to the presence of a large coarse fraction (without a grinding mill it is not possible to obtain a good size distribution using BF dust). The carbon content is very variable both in quantity and in size, depending on the operating conditions of the blast furnace.

Iron dusts present a fine size distribution (100% below 80 microns), and a very low density, in comparison to normal iron ores. Due to the combination of a big specific surface (porosity) and a very small particle size, the pelletising operation was very difficult; the green pellets quality was poor and the total moisture was high (average of 20% w.b.), increasing the decrepitation of pellets in the furnace. For these reasons the iron dusts were used only for few tests, and will be replaced in the future with ground BF pellets fines or commercial iron ore fines.

Figure 8and Figure 9 report the average size distribution of the materials employed.

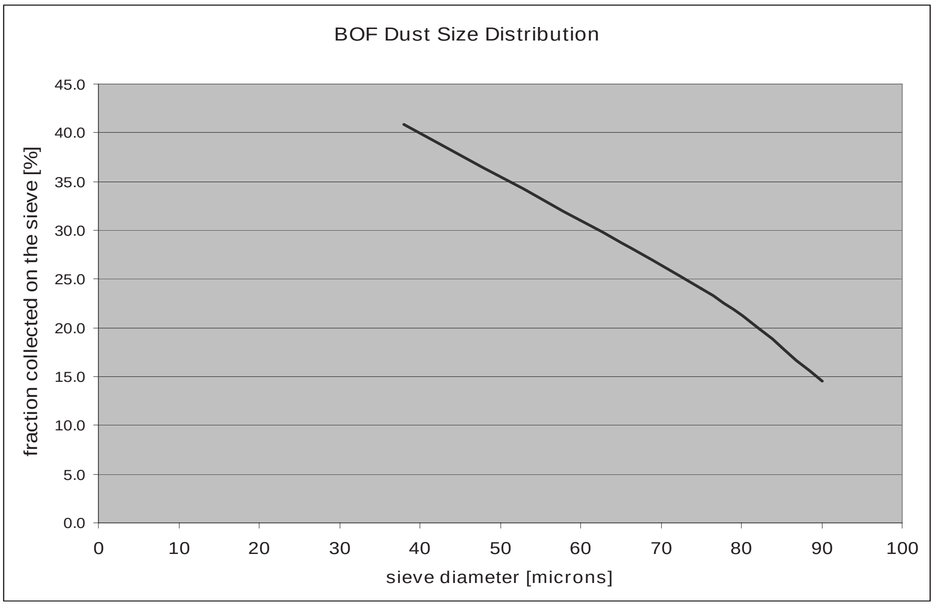


Figure 8. BOF dust – size distribution

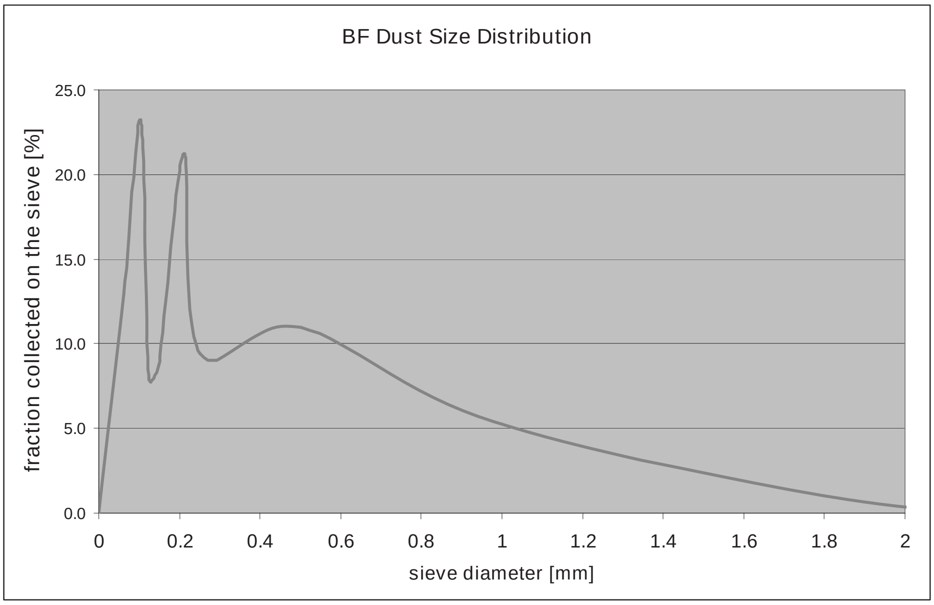


Figure 9. BF dust – size distribution

RHF TESTS CAMPAIGN DATA UTILISATION

Data collected during different campaigns have been used to carry out, for each significant test, two different types of material and energy balance, implemented in 1-D model and supported by CFD simulations implemented by 3D fluid-dynamic simulation tool, in order to define and set the parameters relevant to the RHF direct reduction process (details about the two models are reported in 2.6).

The first overall balance model carries out an overall material and thermal balance, which has the aim of evaluating at first the test data reliability and then to get a set of parameters relevant to the different operating conditions in order to characterise the reduction process.

The second "1-D" model program carries out one-dimensional thermal calculation along the furnace length, aiming at analysing on a local basis the parameters of the reduction process and to simulate alternative operating conditions.

Three-dimensional simulations have been made using 3D CFD model, in order to tune the 1-D model and to characterise the fluid-dynamics of burners and air/gas wickets.

The data, collected for each test, which have been used to carry out the balances are as follows:

- Green pellets mass flow rate
- Green pellets chemical analysis and moisture
- Green pellets physical and mechanical properties
- DRI chemical analysis
- DRI pellets physical and mechanical properties
- 1st, 2nd and 3rd zone fuel flow rates
- 1st, 2nd and 3rd zone burners air flow rates
- 1st and 2nd zone wickets air flow rates
- 1st, 2nd, 3rd zone temperatures of furnace refractory (roof)
- Off gas temperature
- Off gas oxygen content
- Furnace pressure at the discharge point

OVERALL MATERIAL AND THERMAL BALANCE

An overall balance has been carried out for each significant test as shown in Figure 10 (where test data are highlighted) and in Figure 11.

Furnace thermal losses are set at the same value found by the 3D CFD model.

It has to be remarked that some false air enters the furnace from its charging and discharging ends. This flow rate is calculated comparing the oxygen content in the off-gas resulting from the gas material balance and the one measured at the off-gas duct.
Part of this air enters from the green pellets feeder, where the furnace pressure is minimum. As shown by CFD simulations, part of the false air is directly sucked in the off-gas duct, part enters the 1st furnace zone and part flows through the discharge zone and reaches the 3rd heating zone.

Another air inlet is due to the post-combustion air pipes located in the off-gas duct. Even if, during the tests, the post combustion blower is not used, some air is sucked in the duct, due to its draft effect. The energy balance closure is reasonably correct for most of the tests. This confirms the reliability of the measurements and the validity of the tests.

	Nm3/h	kg/h	°C	kW					
Pellets wet In		6388.5	25	-10,713					
Fuel	583	414.3	25	-538					
Air Fuel	6266	8035.1	25	-169					
Air Wickets	2751	3527.6	25	-74					
Air False	1377	1765.6	25	-37	<-----	% O2 off gas		3.61%	
Total IN	10977	20131.1		-11,531					
DRI		4181.0	1001	-2,502	<-----	T screw zone		901	
Off Gas	12548	15950.1	948	-9,888	<-----	T off gas		948	
Roof Wall Losses				237	=	2,016	W/m2 x	117.7	m2
Hearth Wall Losses				51	=	500	W/m2 x	102.3	m2
Side Wall Losses				103	=	1,603	W/m2 x	64.3	m2
Water Seals Losses				369	=	12,637	W/m x	29.2	m
Screw Losses				391	=	71,560	W/m2 x	5.5	m2
Total OUT		20131.1		-11,239					
Balance		0.0		-293					

Green Pellets RD Fe	% wt dry analysis 75.20%	kg/h	kW
Fe tot.	41.61%	2304.6	
Fe met.	2.30%	127.3	0
FeO	19.09%	1057.5	-1,139
Fe3O4		0.0	
Fe2O3	35.25%	1952.3	-2,798
SiO2	3.51%	194.3	-819
SiC		0.0	
Al2O3	0.97%	54.0	-246
CaO	4.43%	245.1	-772
MgO	1.30%	71.8	-298
TiO2	0.09%	4.9	-16
MnO	2.24%	124.2	-187
P2O5	0.23%	12.5	-37
Na2O	0.29%	16.2	-30
K2O	0.29%	16.0	-21
ZnO	0.88%	48.5	-58
NiO	0.00%	0.0	0
Cr2O3	0.09%	5.0	-30
Cu		0.0	
Mo		0.0	
V2O5	0.00%	0.0	0
Co		0.0	
C tot.	24.95%	1381.9	0
LOI	3.80%	210.7	-524
C lib.		0.0	
S	0.30%	16.6	9
SO3		0.0	
Others	0.00%	0.0	0
Total dry		5538.8	-6,966
H2O	13.30%	849.6644	-3,747
Total wet		6388.5	-10,713

DRI Pellets RD Fe	% wt dry analysis 74.92%	% wt dry 74.92%	kg/h	kW
Fe tot.	57.32%	55.12%	2304.6	
Fe met.	36.90%	35.48%	1483.6	278
FeO	26.60%	25.58%	1069.4	-922
Fe3O4		0.00%	0.0	
Fe2O3		0.00%	0.0	0
SiO2	5.22%	4.65%	194.3	-760
SiC		0.00%	0.0	
Al2O3	1.78%	1.29%	54.0	-230
CaO	5.54%	5.86%	245.1	-711
MgO	1.07%	1.72%	71.8	-275
TiO2	0.11%	0.12%	4.9	-15
MnO	1.90%	2.97%	124.2	-163
P2O5	0.16%	0.16%	6.5	-17
Na2O	0.11%	0.11%	4.5	-7
K2O	0.33%	0.32%	13.6	-14
ZnO	0.31%	0.31%	13.1	-13
NiO	0.00%	0.00%	0.0	0
Cr2O3	0.06%	0.12%	5.0	-27
Cu		0.00%	0.0	
Mo		0.00%	0.0	
V2O5	0.00%	0.00%	0.0	0
Co		0.00%	0.0	
C tot.	20.96%	20.96%	876.1	363
LOI		0.00%	0.0	0
C lib.		0.00%	0.0	
S	0.36%	0.36%	14.9	11
SO3		0.00%	0.0	
Others	0.00%	0.00%		0
Total		100.00%	4181.0	-2,502

Off gas	% vol	kg/h	kW
CO2	12.93%	3186.3	-6,998
SO2	0.01%	3.4	-4
H2O	18.37%	1853.2	-5,903
N2	65.07%	10204.8	2,917
O2	3.61%	646.8	172
P2O5		6.0	-16
Na2O		11.8	-18
K2O		2.4	-2
ZnO		35.4	-37
Total	100.00%	15950.1	-9,888

Figure 10. Typical RHF overall balance

TEST		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
GP	kg/h	5811	6165	6064	6164	6172	6014	6388	6313	6385	6437	7086	6255	5178	4438	4761	6700	7177	6935	6912	6847	7057	7529	6675
PAF	%	60.0%	60.0%	60.0%	60.0%	65.0%	65.0%	60.0%	60.0%	60.0%	50.0%	50.0%	50.0%	50.0%	50.0%	50.0%	65.0%	65.0%	65.0%	50.0%	50.0%	50.0%	50.0%	50.0%
Hearth Charge	Kg/m2	24.73	25.44	21.09	20.30	15.88	15.61	16.57	24.17	24.44	16.78	21.43	17.91	15.12	15.71	16.85	17.67	18.99	18.35	18.12	17.95	21.81	26.64	17.47
Hearth rotation speed	giri/h	2.38	2.38	2.81	3.00	3.77	3.76	3.76	2.50	2.50	3.76	3.15	3.22	3.22	2.81	2.81	3.76	3.76	3.76	3.75	3.75	3.21	2.81	3.75
Useful residence time	min	21.97	21.97	18.56	17.41	13.87	13.89	13.91	20.90	20.90	13.91	16.57	16.25	16.25	18.58	18.58	13.91	13.91	13.91	13.91	13.91	16.25	18.58	13.91
Hstrato	mm	15.93	16.91	14.05	13.40	10.68	10.42	11.09	16.47	16.65	11.17	14.65	12.68	10.50	10.29	11.04	11.63	12.46	12.04	12.00	11.89	14.31	17.46	11.59
%H2O green pellets	%	9.9%	12.6%	12.8%	12.0%	13.7%	13.1%	13.3%	14.8%	14.8%	12.8%	15.1%	18.0%	16.4%	11.4%	11.4%	11.8%	11.5%	11.6%	12.4%	12.4%	11.6%	11.4%	12.5%
%C green pellets	%	19.93%	21.43%	19.40%	22.42%	27.22%	24.38%	24.95%	28.53%	25.13%	16.15%	18.50%	13.80%	15.40%	14.06%	14.06%	21.69%	20.19%	19.92%	14.25%	14.25%	18.97%	17.48%	17.40%
%Fe green pellets	%	45.44%	44.54%	45.44%	44.40%	40.50%	42.00%	41.61%	39.06%	41.23%	44.81%	45.47%	54.48%	54.65%	49.50%	49.50%	44.15%	45.41%	45.43%	49.25%	49.25%	46.20%	47.84%	46.59%
RD green pellets	%	15.43%	15.67%	15.55%	15.74%	14.77%	14.68%	15.95%	15.71%	15.81%	18.45%	17.01%	6.45%	6.41%	7.10%	7.10%	13.93%	15.00%	15.74%	18.04%	18.04%	23.58%	18.94%	19.78%
%C DRI	%	13.48%	16.48%	10.66%	14.47%	20.06%	15.95%	20.96%	20.63%	20.74%	7.89%	6.92%	6.97%	1.40%	2.18%	4.40%	17.49%	11.55%	11.22%	5.87%	10.41%	13.45%	7.48%	8.27%
%Fe DRI	%	60.48%	56.55%	62.70%	62.00%	58.49%	62.21%	55.12%	54.73%	54.96%	65.25%	65.22%	73.72%	84.05%	74.47%	68.58%	56.06%	61.87%	65.66%	67.37%	61.14%	57.32%	67.82%	65.37%
RD DRI	%	64.29%	54.31%	71.16%	75.37%	83.94%	86.57%	74.92%	81.32%	78.17%	82.44%	74.82%	63.84%	79.66%	82.99%	65.84%	58.64%	58.68%	77.83%	62.71%	49.17%	47.13%	76.56%	77.80%
GP MIX dry	kg/h	5234	5386	5285	5422	5325	5228	5539	5379	5440	5613	6016	5127	4327	3933	4219	5909	6350	6133	6058	6001	6242	6669	5839
DRI	kg/h	3933	4242	3830	3882	3687	3529	4181	3839	4082	3855	4194	3789	2814	2614	3045	4654	4660	4244	4429	4834	5031	4704	4162
C/O		1.36	1.51	1.43	1.40	1.47	1.39	1.14	1.65	1.14	1.14	1.58	0.86	1.12	1.02	1.13	1.22	1.80	1.32	1.37	1.15	2.20	1.36	1.30
Fuel	Nm3/h	491	399	569	534	530	524	583	616	616	787	726	761	573	423	467	374	479	484	505	433	470	474	505
	1st zone	0	0	0	0	0	0	0	0	0	0	0	107	0	0	43	12	0	0	0	0	0	0	0
	2nd zone	261	270	276	244	254	248	256	300	300	289	275	260	225	138	194	157	205	213	254	186	117	145	150
	3rd zone	231	129	293	290	276	276	327	316	316	498	451	395	347	285	229	205	274	270	251	248	353	329	355
Air Burners	Nm3/h	5133	4078	5968	5638	5767	5755	6266	5770	5773	6934	6708	7266	5604	4431	4974	4561	5722	5758	5872	5403	5088	5240	5736
	1st zone	0	0	0	0	0	0	256	400	400	253	251	1148	258	618	1024	830	776	777	847	850	502	504	507
	2nd zone	2603	2658	2686	2440	2687	2672	2435	2490	2493	2476	2399	2434	2100	1379	1859	1660	2156	2244	2544	2139	1304	1614	1650
	3rd zone	2530	1420	3282	3198	3080	3083	3576	2880	2881	4205	4058	3684	3246	2435	2090	2071	2790	2737	2481	2414	3282	3122	3578
Air Wickets	Nm3/h	4299	2150	4301	2550	2550	2550	2751	3389	3601	4784	4500	4501	4500	3472	3499	2050	2049	2049	2252	2501	2499	2500	2501
	1st zone	2599	1300	2600	1550	1550	1550	1000	1888	2101	3000	3000	3001	3000	2472	2500	1250	1250	1249	1250	1501	1250	1250	1251
	2nd zone	1700	850	1700	1000	1000	1000	1751	1500	1500	1784	1500	1500	1500	1000	1000	800	800	800	1002	1000	1250	1250	1250
	3rd zone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Rate	Nm3/t GP	93.9	74.0	107.7	98.5	99.6	100.2	105.3	114.6	113.3	140.2	120.7	148.5	132.4	107.5	110.6	63.4	75.5	78.9	83.4	72.2	75.3	71.0	86.5
False Air	Nm3/h	5242	5026	3160	2972	3531	3297	1377	3601	1549	864	3108	510	3264	3215	2993	2969	5467	3878	4343	3677	4084	5567	4013
%O2 off gas	%	8.79%	7.34%	5.74%	3.45%	3.67%	3.63%	3.61%	2.91%	3.64%	2.64%	2.67%	4.53%	6.23%	7.67%	7.30%	6.23%	5.00%	4.16%	5.77%	8.48%	5.45%	5.37%	5.17%
End furnace pressure	mm H2O	-0.70	-0.60	-0.64	-0.60	-0.59	-0.61	-0.21	-0.01	0.02	-0.29	-0.11	0.16	-0.26	-0.28	0.18	-0.25	-0.17	-0.30	-0.34	-0.30	-0.20	-0.23	-0.19
Green pellets >4.75								92.05%	92.11%	89.54%	96.80%	98.09%	94.62%	96.39%	99.59%	99.59%	69.50%	94.34%	97.08%	97.68%	97.68%	68.81%	90.38%	83.39%
DRI >4.75								58.20%	68.71%	64.32%	71.45%	41.55%	76.28%	75.34%	62.83%	86.35%	28.17%	42.35%	41.11%	59.84%	80.69%	51.93%	86.98%	67.03%
Compress Eq Medium								16	22	24	30	44	49	116	93	24	27	19	32	31	20	28	14	28
Offgas Zone	℃	938	957	937	1011	978	991	953	1016	1023	1088	1080	1007	957	949	964	932	947	953	936	872	919	914	911
1st Zone	℃	1172	1189	1179	1209	1184	1196	1173	1216	1221	1288	1280	1241	1222	1194	1203	1184	1189	1205	1196	1109	1176	1174	1157
2nd Zone	℃	1268	1268	1263	1267	1247	1256	1259	1272	1269	1359	1347	1313	1329	1311	1308	1259	1265	1265	1269	1214	1242	1248	1236
3rd Zone	℃	1295	1231	1289	1295	1281	1288	1286	1264	1256	1350	1344	1305	1349	1349	1307	1293	1303	1301	1303	1281	1288	1296	1282
Screw Zone	℃	684	664	773	787	776	797	901	907	898	979	942	954	961	912	874	842	883	880	889	839	876	878	885
%CO + %H2	2nd Zone	1.2%	0.9%	1.0%	0.0%	4.5%	6.4%	0.3%	0.3%	0.3%	0.3%	0.6%	0.9%	0.7%	0.2%	0.5%	2.2%	4.0%	4.4%	5.3%	0.3%	6.7%	8.4%	8.9%
%CO + %H2	3rd Zone	2.0%	0.6%	1.7%	0.5%	0.2%	0.1%	5.1%	9.6%	8.3%	10.4%	8.8%	5.4%	2.5%	1.9%	4.3%	1.0%	2.9%	3.0%	1.2%	0.2%	3.9%	3.2%	4.7%
%O2	2nd Zone	3.2%	4.4%	6.9%	3.5%	3.0%	2.7%	20.3%	20.5%	20.6%	20.5%	19.8%	7.1%	7.5%	7.7%	7.6%	7.4%	7.1%	6.8%	9.8%	14.2%	6.9%	7.1%	6.9%
%O2	3rd Zone	10.0%	10.4%	5.4%	10.4%	6.2%	5.8%	6.6%	5.1%	7.6%	4.9%	4.5%	4.1%	4.8%	5.9%	5.9%	6.2%	5.8%	4.7%	7.5%	13.9%	5.4%	6.0%	5.8%
Heat Balance (in-out)	kW	-465	-734	245	271	399	214	-293	807	-520	401	824	-880	-404	-900	-669	-1346	371	-6	-416	-1596	56	82	57
OFFgas	Nm3/h	16362	13031	15484	13164	14002	13708	12548	15020	13221	15046	16953	15020	15585	12653	13018	11401	15294	13847	14611	13517	13526	15555	14403
TDRI	℃	784	764	873	887	876	897	1001	1007	998	1079	1042	1054	1061	1012	974	942	983	980	989	939	976	978	985
Toffgas	℃	808	831	899	983	961	985	948	1002	996	1055	1052	984	902	862	880	862	894	913	886	792	860	843	858

Figure 11. Overall balance of RHF significant tests

TESTS CAMPAIGN DATA ANALYSIS

In the following pages the results of the tests analysis are reported. The dispersion of the data is due to the representation of only one parameter for each graph, so the simultaneous effects of other variables are neglected. Other reasons for the dispersion of the data are due to non-measurable effects such as the quality of charge distribution across the hearth. In some tests the distribution was not uniform due to the sticking of wet green pellets in the preparation circuit and in the feeding system. These instabilities, when they occur, affect negatively both the pellets reduction and the mechanical strengthening of the DRI. Another reason of the worsening of DRI quality is due to some instability in the balling operation, resulting in not optimal size distribution, with consequent decrepitation of pellets and/or higher amount of fines generated in the furnace.

DRI PELLETS REDUCTION DEGREE

Figure 12 shows the DRI pellets reduction versus green pellets carbon content. The increase of carbon content in green pellets produces a slightly higher metallisation.

Figure 13 shows the DRI pellets reduction versus furnace temperature: the reduction degree, as expected, grows increasing the furnace temperature.

Figure 14 shows the DRI pellets reduction degree versus the total energy given to the furnace. This energy is calculated taking into account the calorific value of natural gas plus that of carbon consumed in the process.

Reporting the same relationship separating the contributions of natural gas and carbon combustion, it is clear that they contribute in a similar way to the process and that the carbon consumption is very closely related to the reduction degree (Figure 15 and Figure 16).

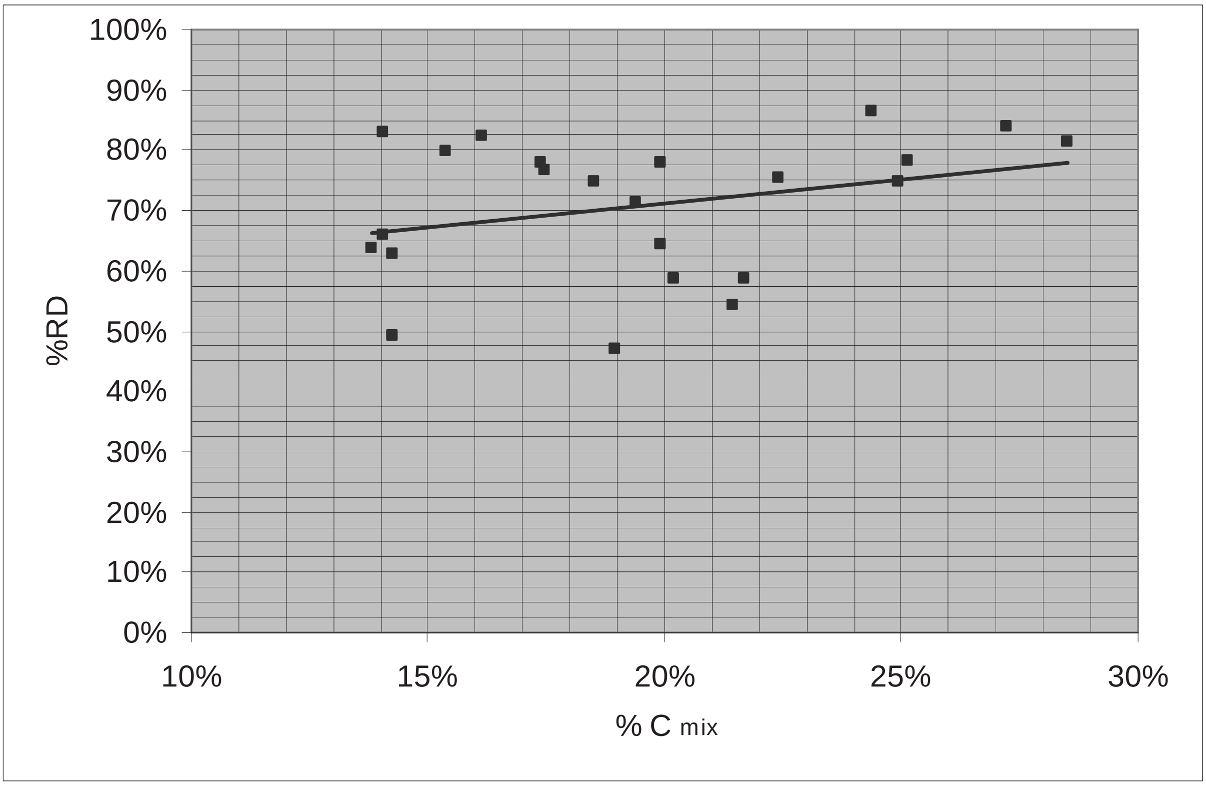


Figure 12. DRI reduction degree as a function of carbon content in green pellets

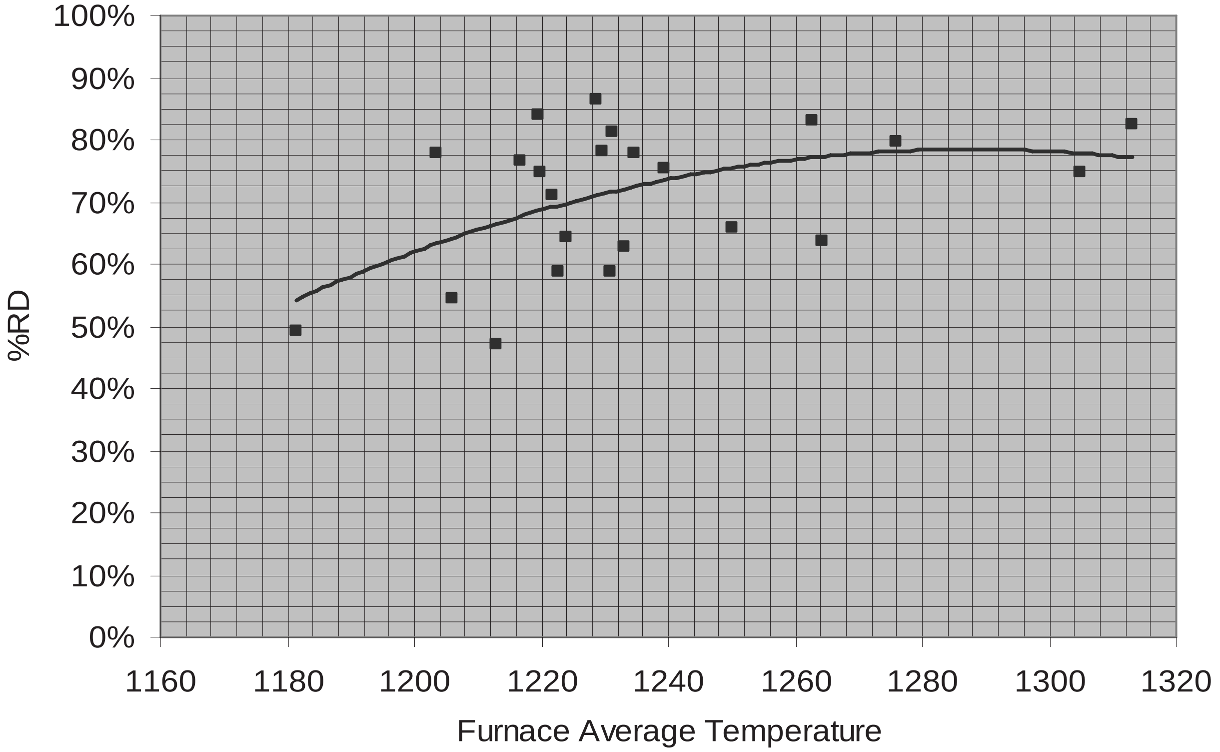


Figure 13. DRI reduction degree as a function of furnace temperature

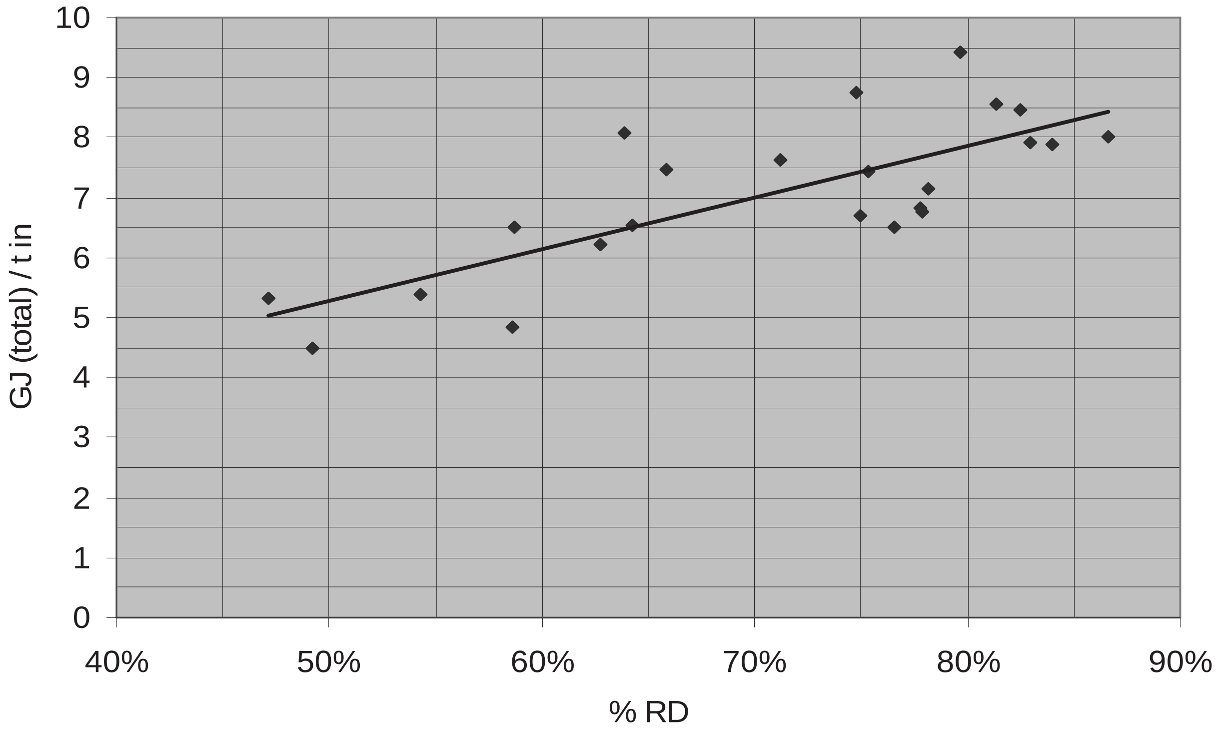


Figure 14. Energy given to the furnace as a function of DRI reduction degree

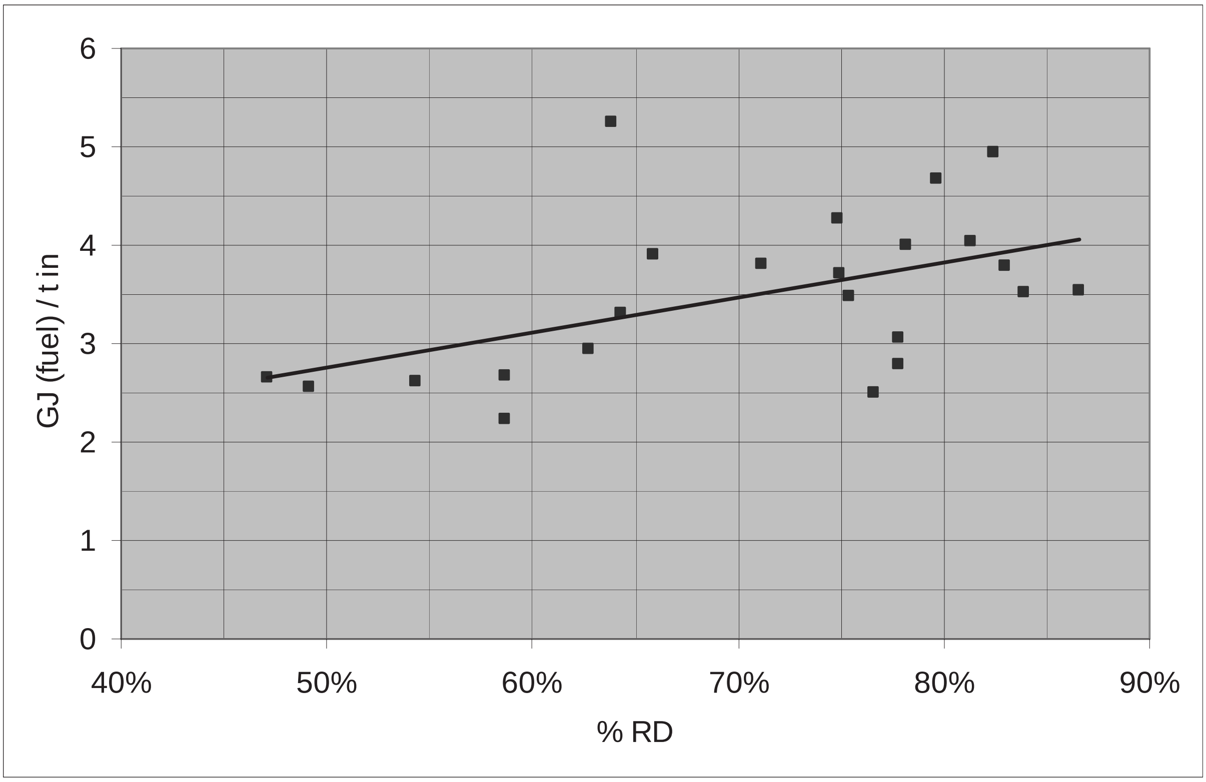


Figure 15. Energy given by natural gas as a function of the DRI reduction degree

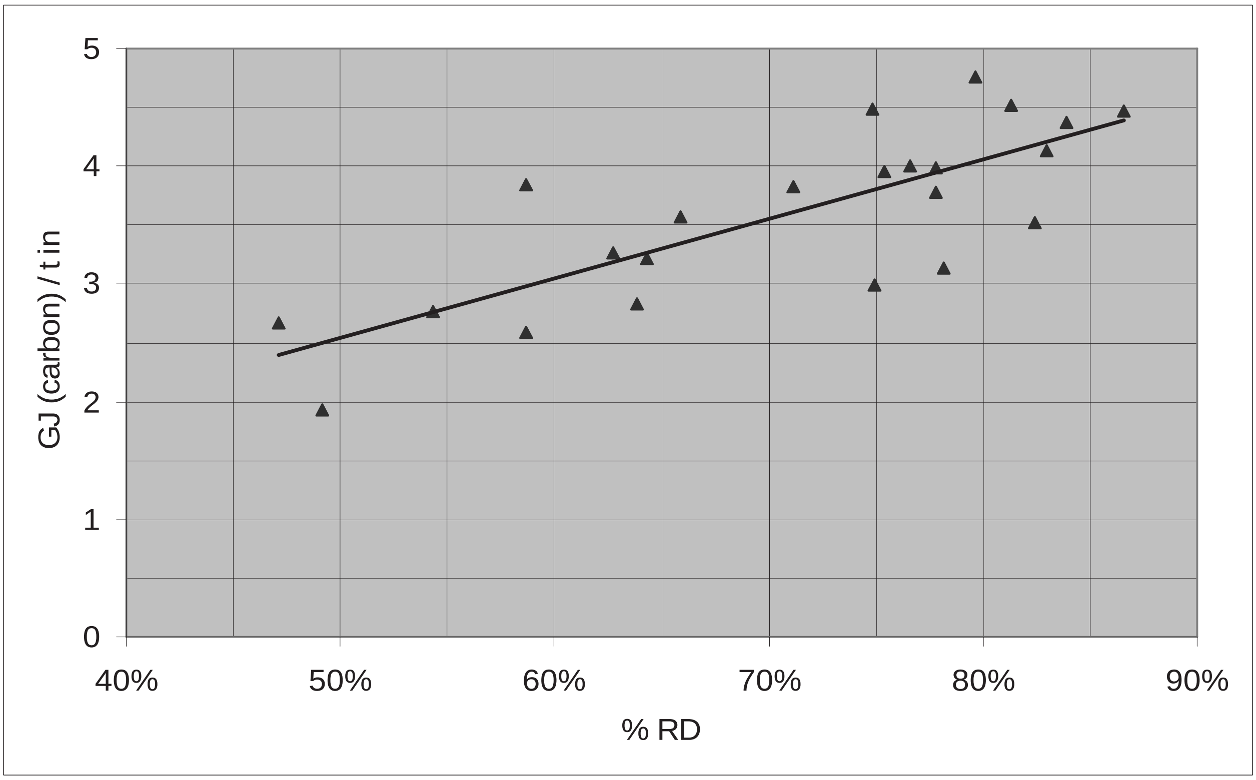


Figure 16. Energy given by carbon as a function of the DRI reduction degree

Anyway the consumed carbon quantity exceeds the quantity needed for reduction of Fe (which is about 1.0 mol of C / mol O removed from oxides as discussed below). The excess quantity of carbon is burnt by oxygen or carbon dioxide and is called “carbon burnout”.

Figure 17 shows that the ratio between the carbon burnout and the total carbon available in the green pellets is not dependent on the furnace temperature:

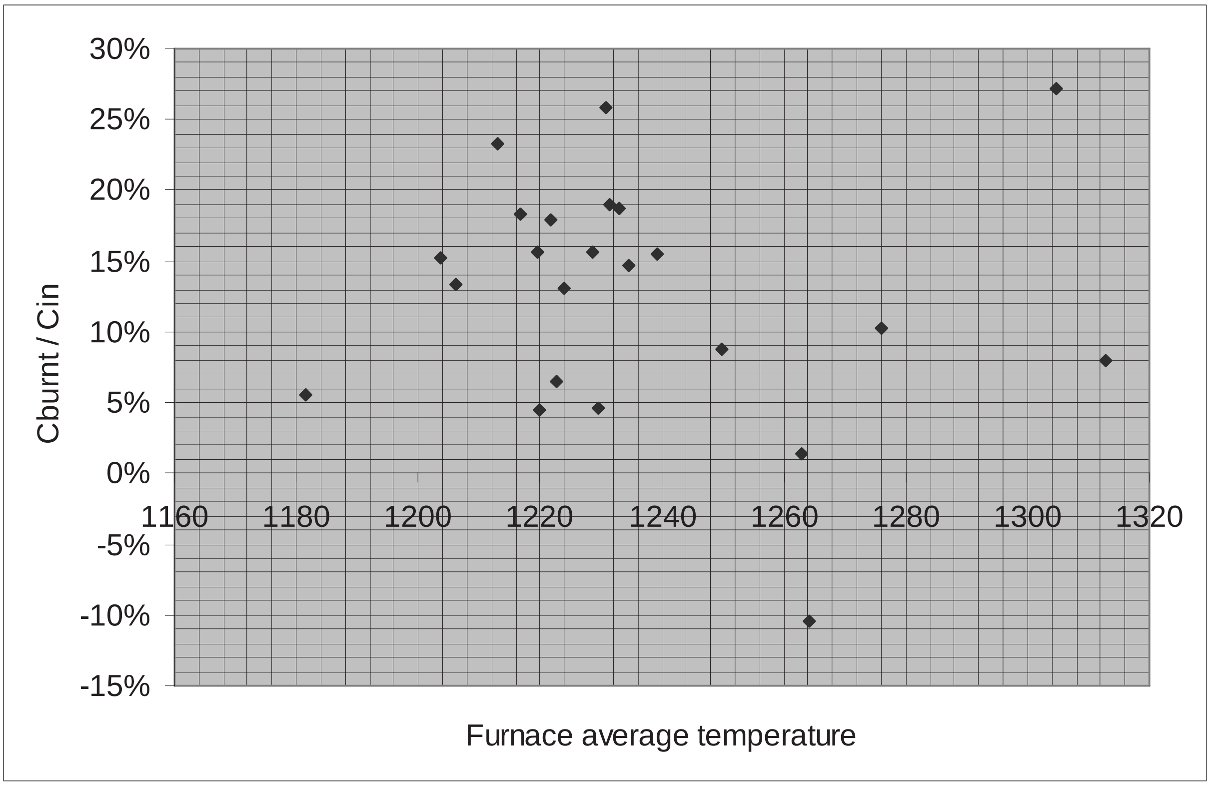


Figure 17. Carbon burnout at different furnace temperatures

RATIO C/O

The consumption of carbon in the furnace is one the most relevant parameters of the process. The carbon is consumed both by the reaction of reduction process, involving the oxygen from ferrous and non ferrous oxides and by the reaction with the oxygen present in the gas phase, in form of carbon dioxide or free oxygen.

Great part of carbon is consumed by the reduction reaction, which consists of removing oxygen from oxides, producing CO and CO_2; in competition with the reduction, the carbon reacts burning with oxygen or carbon dioxide present in the gas. The stoichiometries of these reactions are the following:

$Fe_aO^* + b\,C = a\,Fe + (1-b)\,CO_2^* + (2b-1)\,CO^*$ reduction reaction

$C + O_2 = CO_2$ burn out by O_2

$C + CO_2 = 2\,CO$ burn out by CO_2

The b value in the reduction reaction is related to bed temperature and to the reaction degree; this value is ranging between 0.5 (correspondent to only CO_2 producing) and 1 (correspondent to only CO producing) and is limited by the well-known FeO_x-Fe-CO-CO_2 chemical equilibria. The * superscript means that the oxygen comes from metal oxides.

The ratio measured in the tests, [Carbon used (C)] / [oxygen removed from oxides (O*)] is increased by the burnout reactions and can reach values much higher then 1.
This fact strongly affects the furnace thermal balance and then the reduction process.

The carbon combustion has different effects on reduction reaction: burning carbon increases the bed temperature, speeding the kinetics of reduction rate, but also consumes the reactant necessary for the removal of oxygen from the oxides.

Due to these reasons this ratio has been analysed in relationship with all various parameters of the test conditions.

The ratio C/O increases slightly with the DRI carbon content (Figure 18) and shows a slight decrease with the reduction degree and the furnace temperature (Figure 19 and Figure 20).

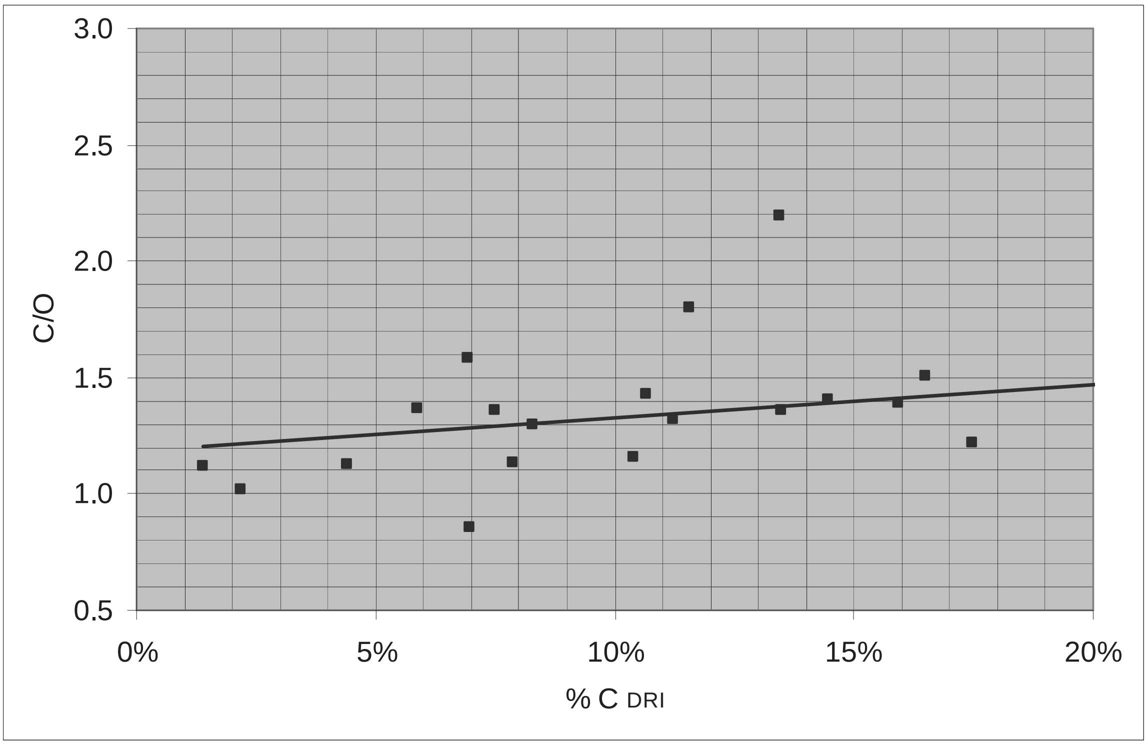


Figure 18. C/O ratio as a function of carbon content in DRI

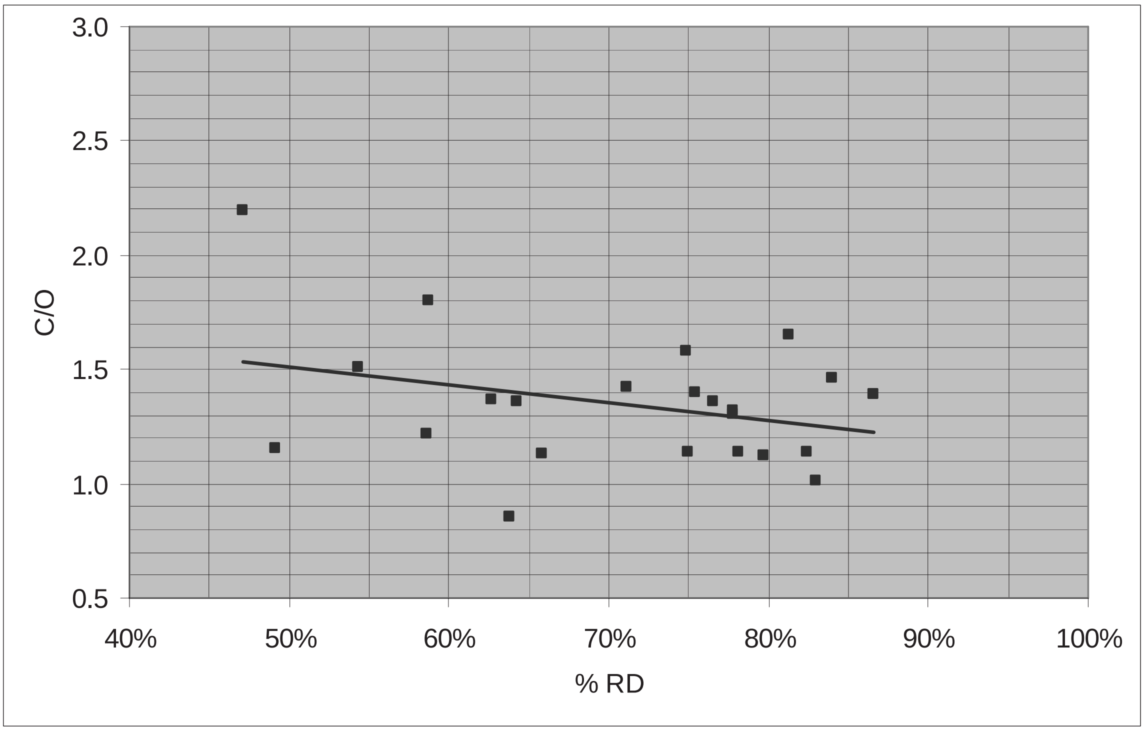


Figure 19. C/O ratio as a function of the reduction degree

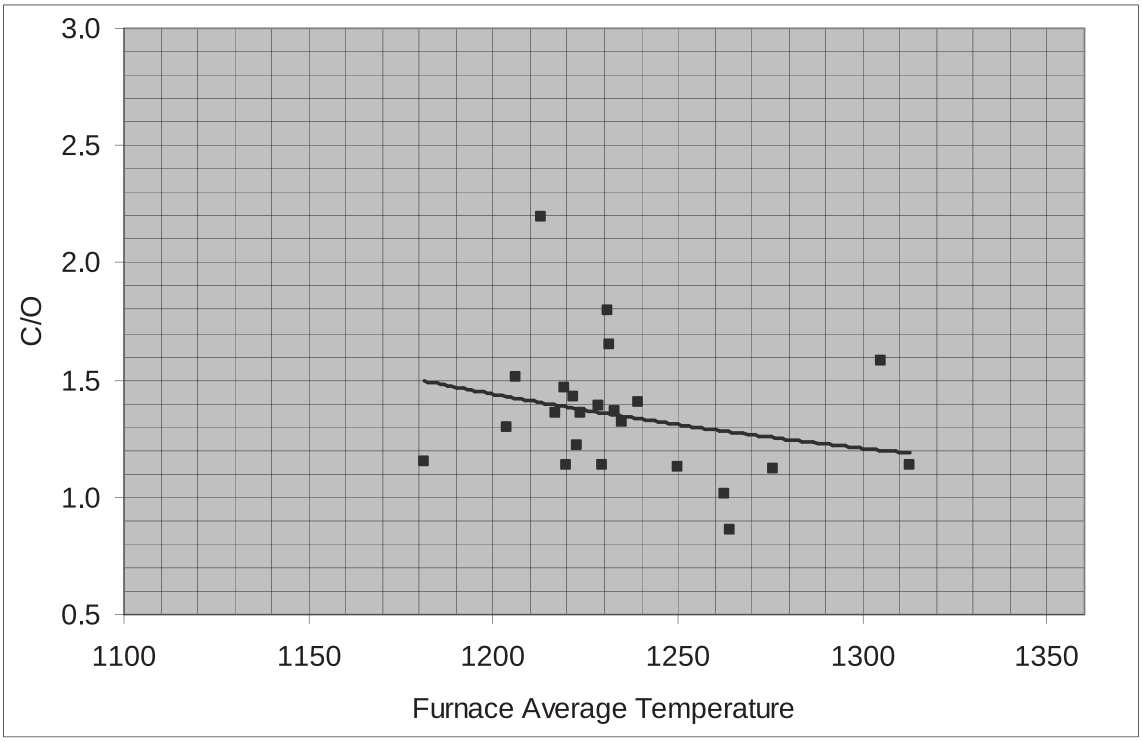


Figure 20. C/O ratio as a function of the furnace temperature

NON-FERROUS OXIDES REDUCTION AND VOLATILES ELEMENTS REMOVAL

Zinc and alkalis are removed in the RHF with an efficiency that may be related with iron reduction (Figure 21 and Figure 22).

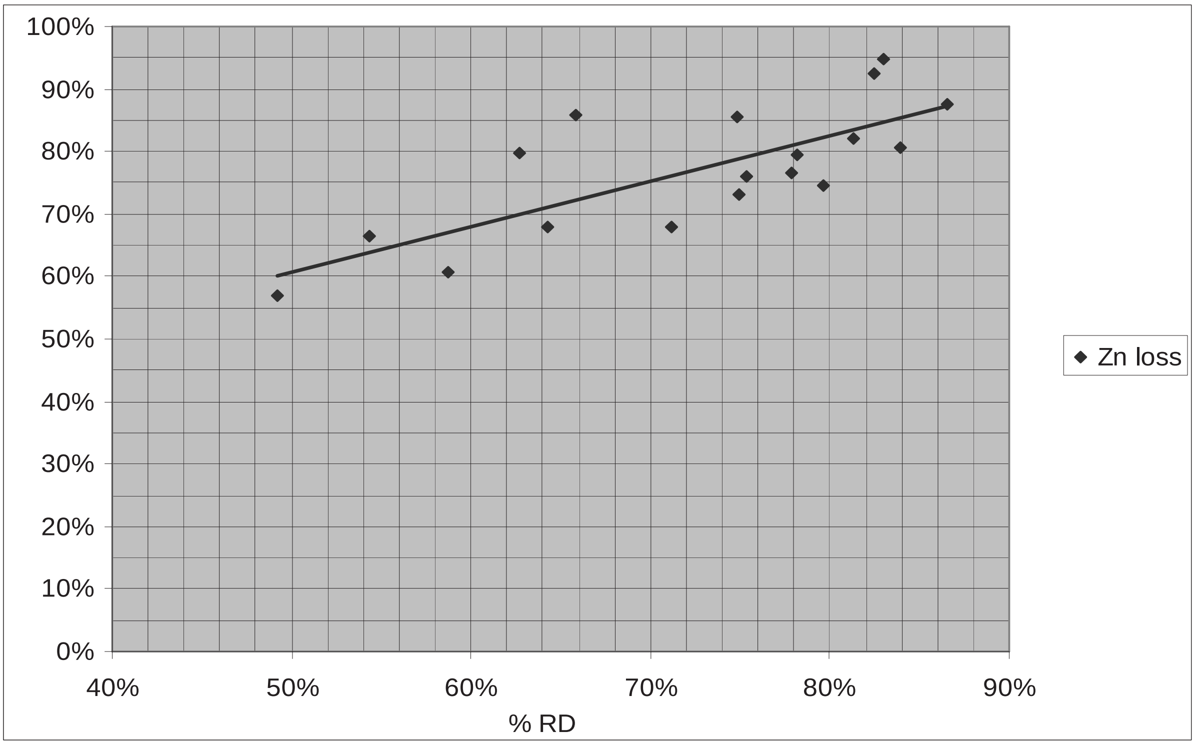


Figure 21. Zinc removal as a function of the reduction degree

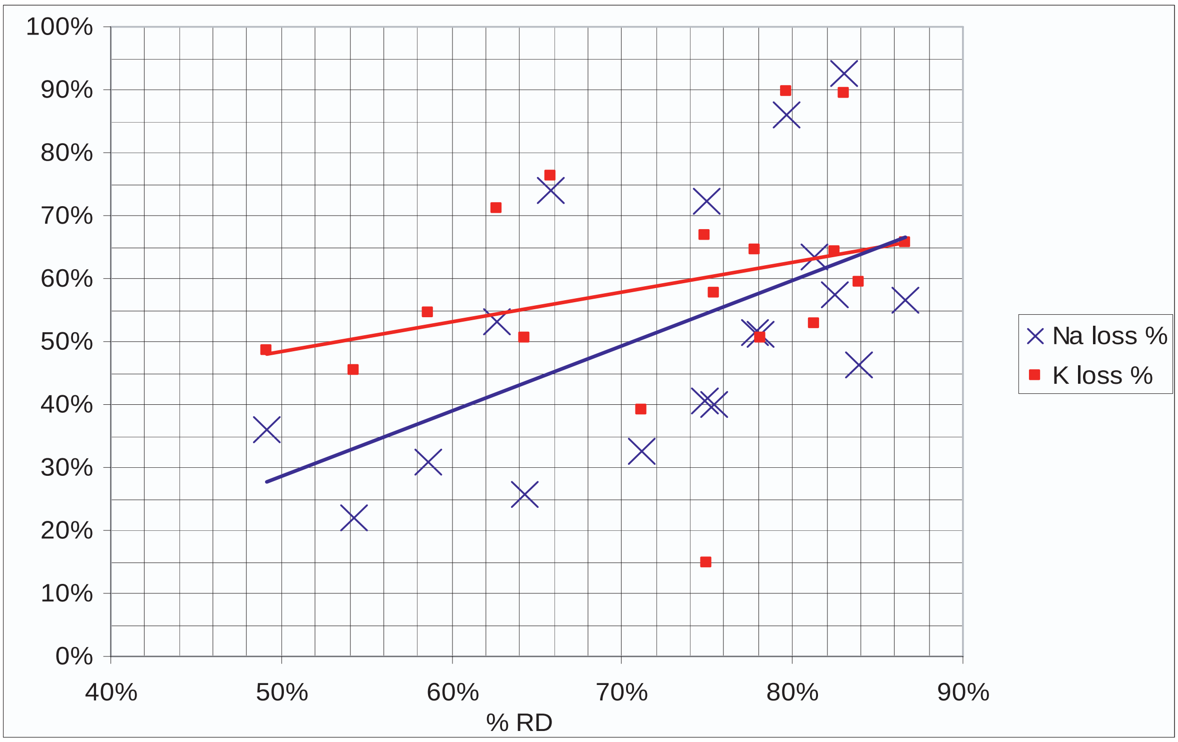


Figure 22. Alkalis removal as a function of reduction degree

Sulphur removal is less variable and seems not so well correlated to the iron reduction (Figure 23).

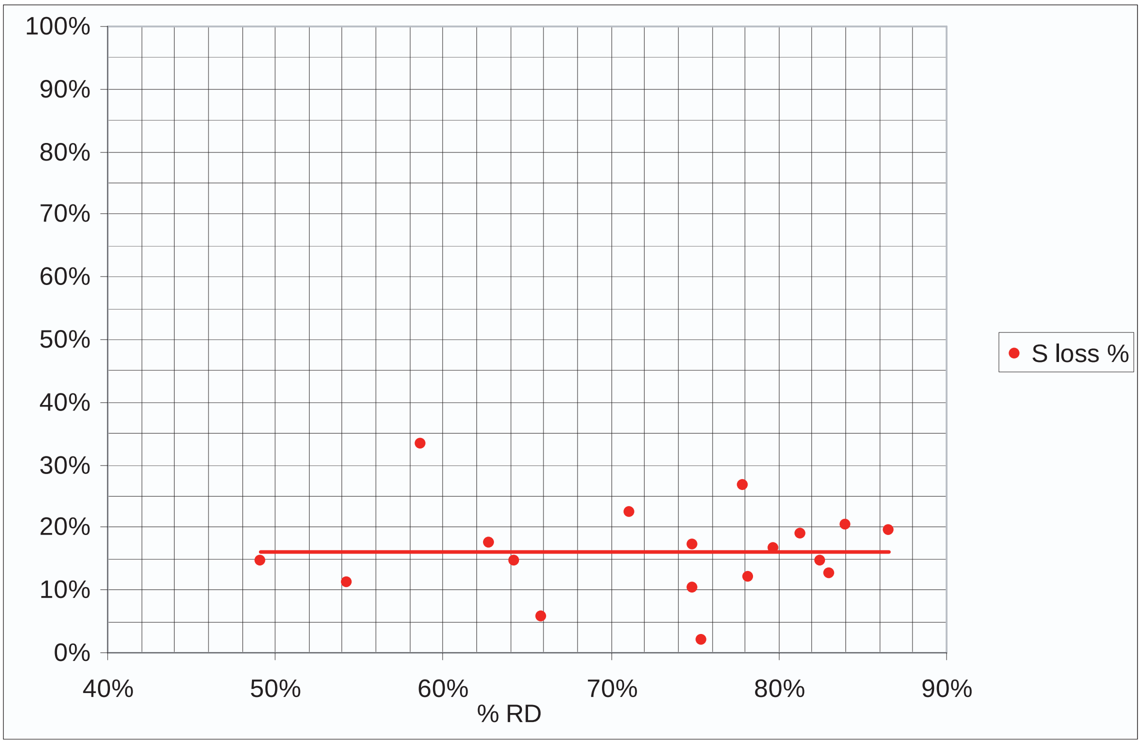


Figure 23. Sulphur removal as a function of reduction degree

DRI PELLETS PHYSICAL AND MECHANICAL CHARACTERISTICS

The fraction of fines in the DRI could be assumed as a good index of DRI mechanical quality.
A higher fines presence in the bed pellets corresponds to a worse thermal exchange between the gas phase and the bed, and, as a consequence, to a lower final reduction degree. The fines could be generated by decrepitation, if the green pellets quality is poor, or when the distribution across the bed is not uniform. In these cases the DRI metallisation is low and carbon burnout is generally higher

In some cases a significant contribution to the fines fraction is due to the extraction screw. In these cases the DRI metallisation could be satisfactory but its mechanical strength is poor due to its high content in carbon (see next figures) or to the lower temperature of the furnace.

Figure 24 shows that DRI quality improves when the reduction degree is higher (DRI, in fact, has a lower amount of fines).

Another fundamental factor affecting the DRI quality is its carbon content (a higher carbon in DRI corresponds to a higher amount of DRI fines, Figure 26 and Figure 27). Green pellets with high carbon often produce DRI of low mechanical quality (Figure 25).

A higher fraction of BF dust (PAF) involves more fines in the DRI, due both to the higher carbon content and to the coarse size of the PAF particles, that cause consequent lower resistance of the green pellets (Figure 28).

Another characteristic that determines the DRI pellets quality is their compression strength.
As expected this parameter increases with the reduction degree (Figure 29), with the furnace 3rd zone temperature (Figure 30) and decreases with the pellets carbon content (Figure 31). Also in this case the carbon content is one of the fundamental parameters determining the DRI quality.
The lower compression strength of DRI pellets with higher BF dust is mainly due to their higher content of carbon (Figure 32).

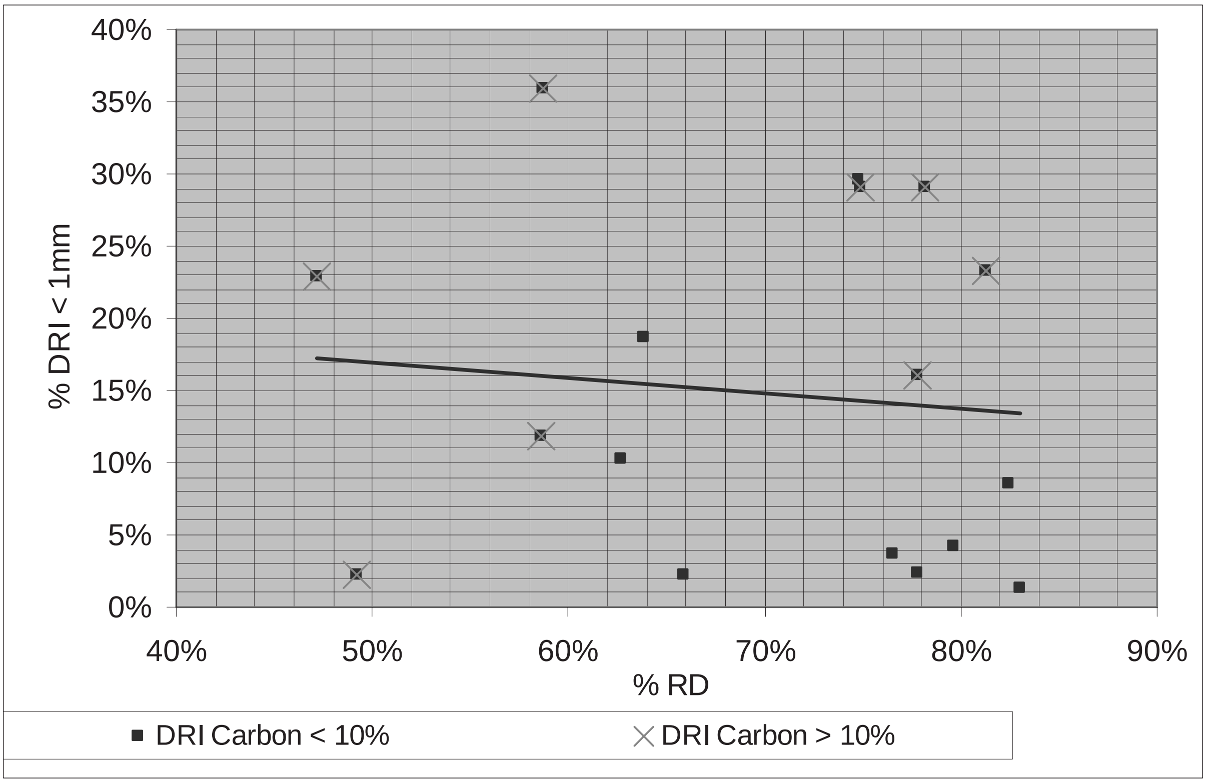


Figure 24. DRI fines below 1 mm as a function of the reduction degree

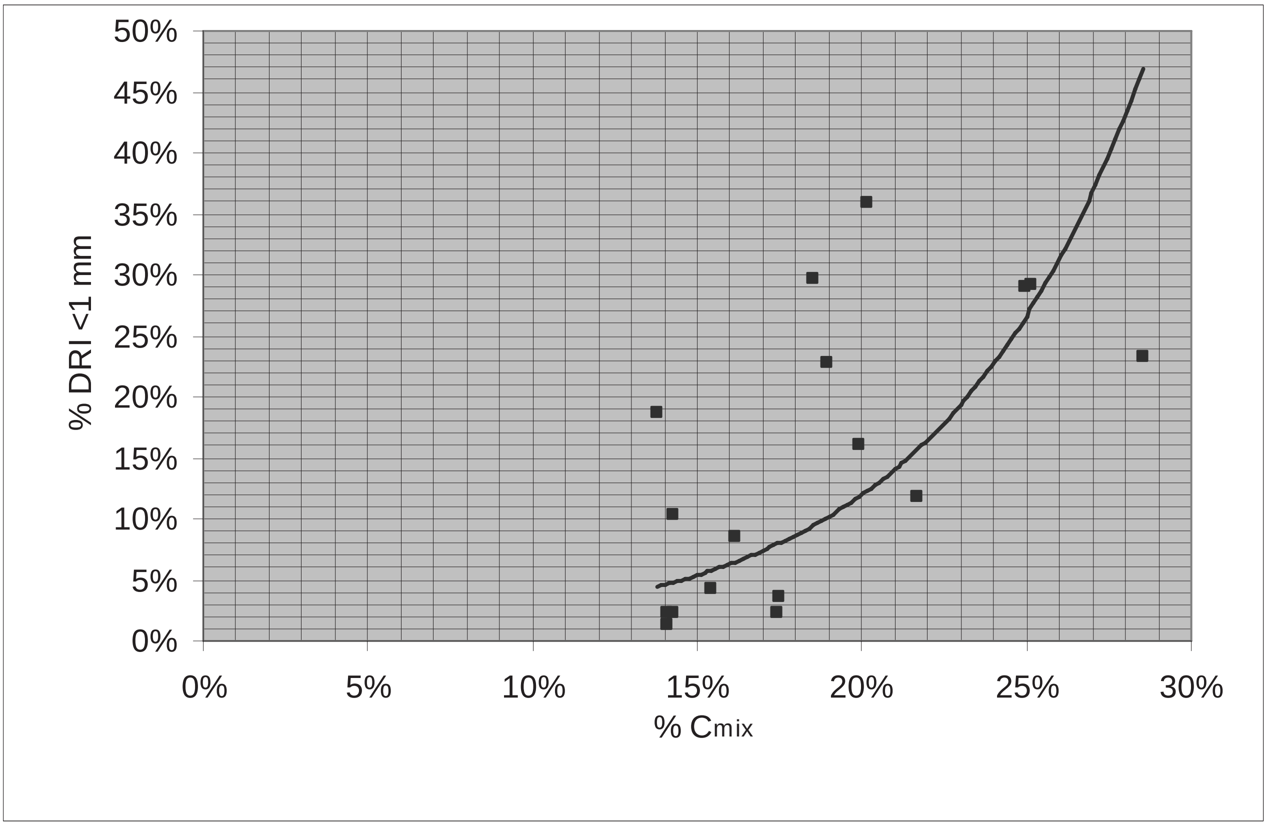


Figure 25. DRI fines below 1 mm as a function of carbon content in the green pellets

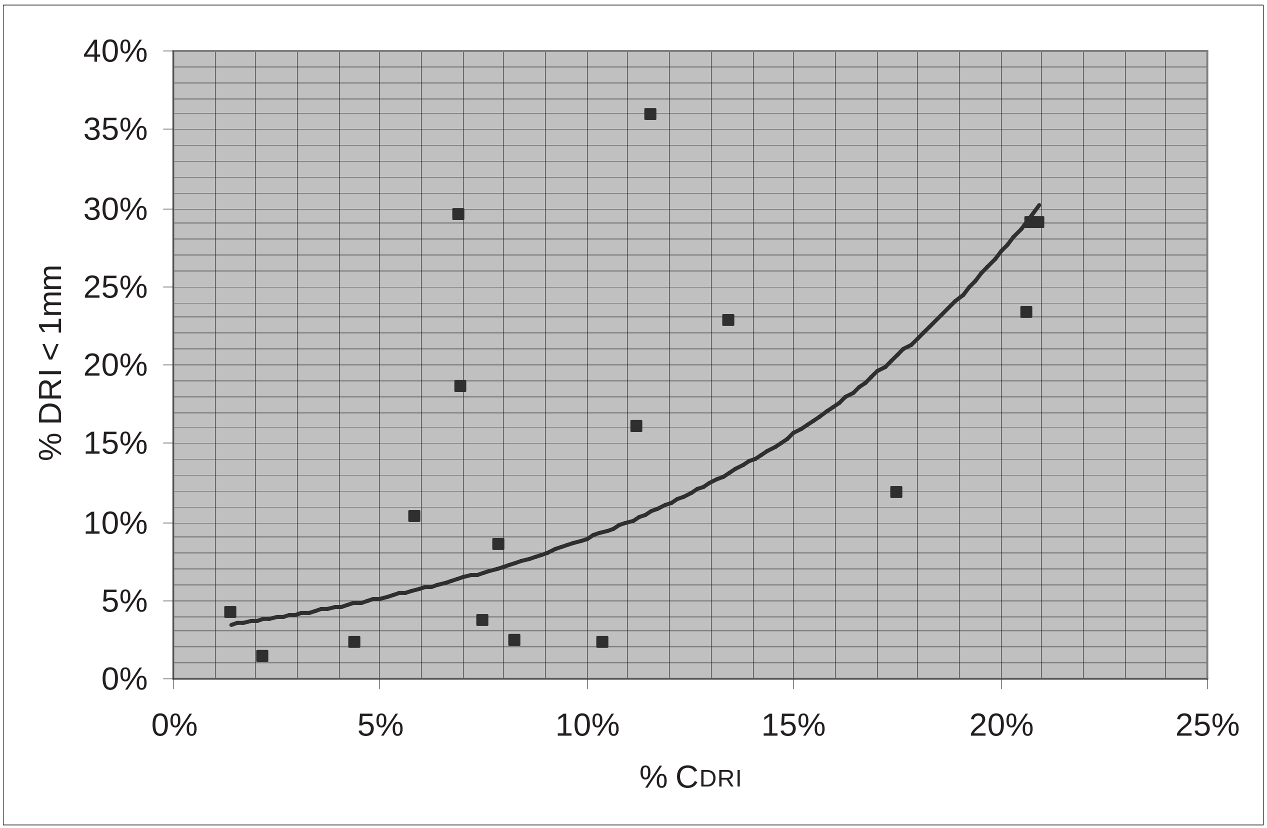


Figure 26. DRI fines below 1 mm as a function of carbon in DRI

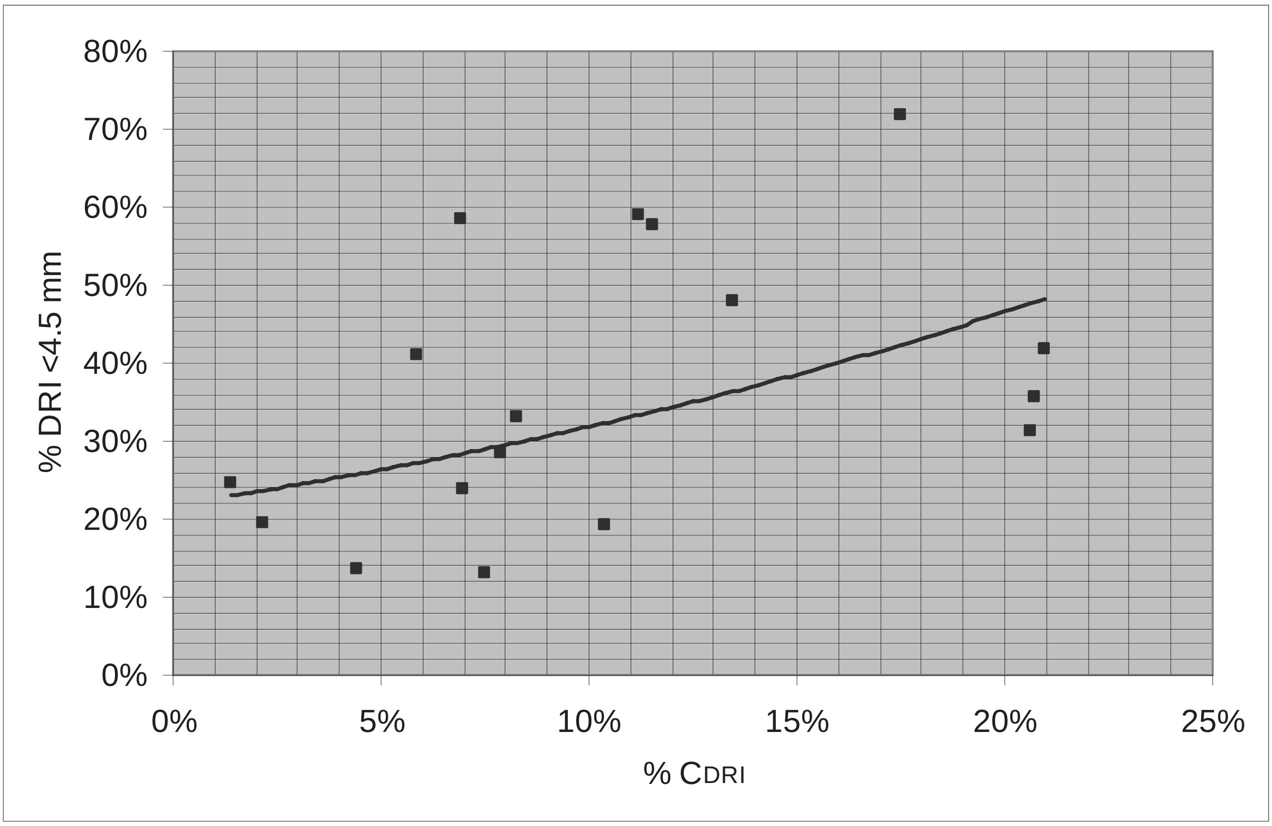


Figure 27. DRI fines below 4 mm as a function of carbon in DRI

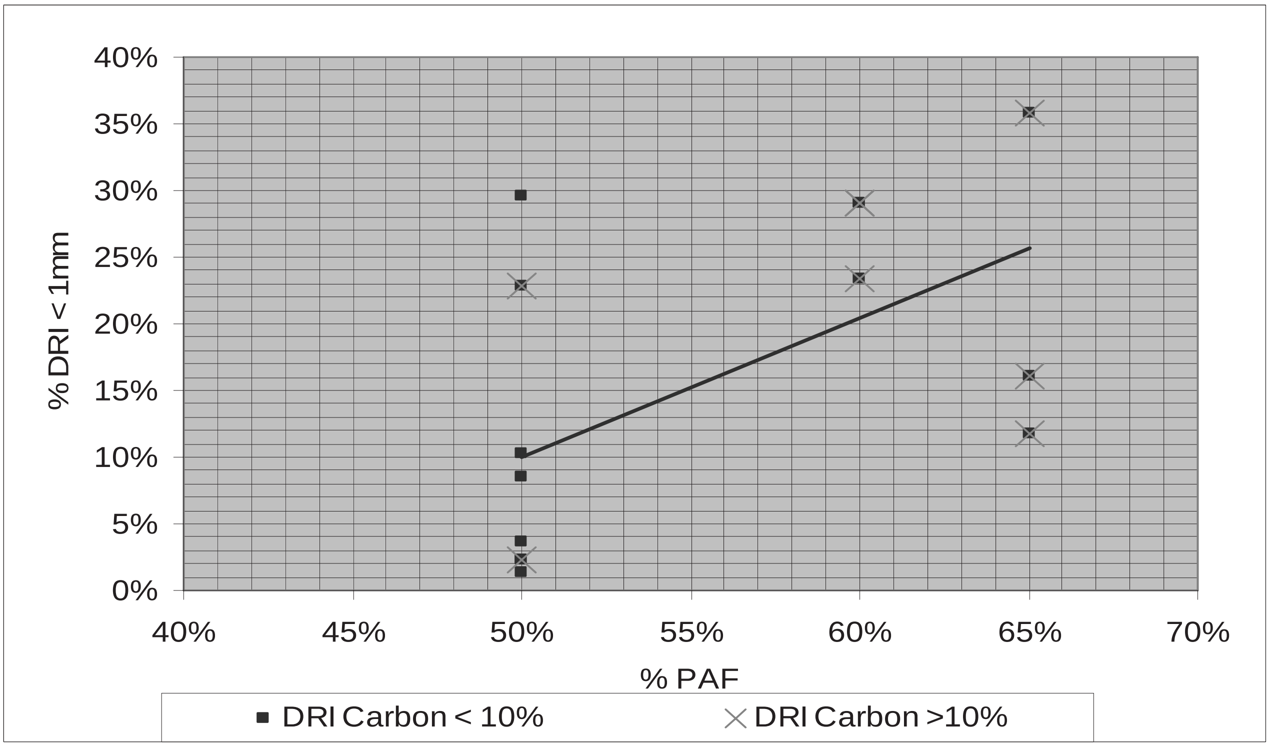


Figure 28. DRI fines below 1 mm as a function of percentage of BF dust in charge

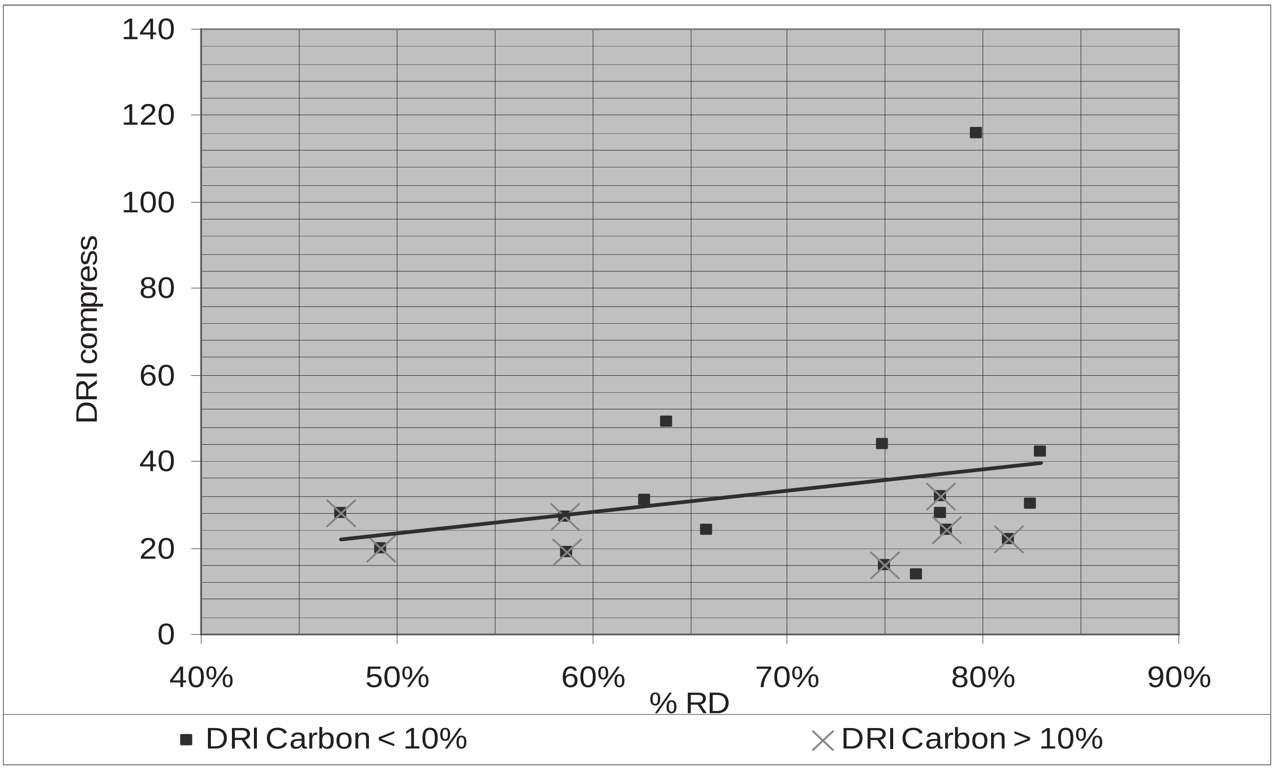


Figure 29. DRI compression strength as a function of the reduction degree

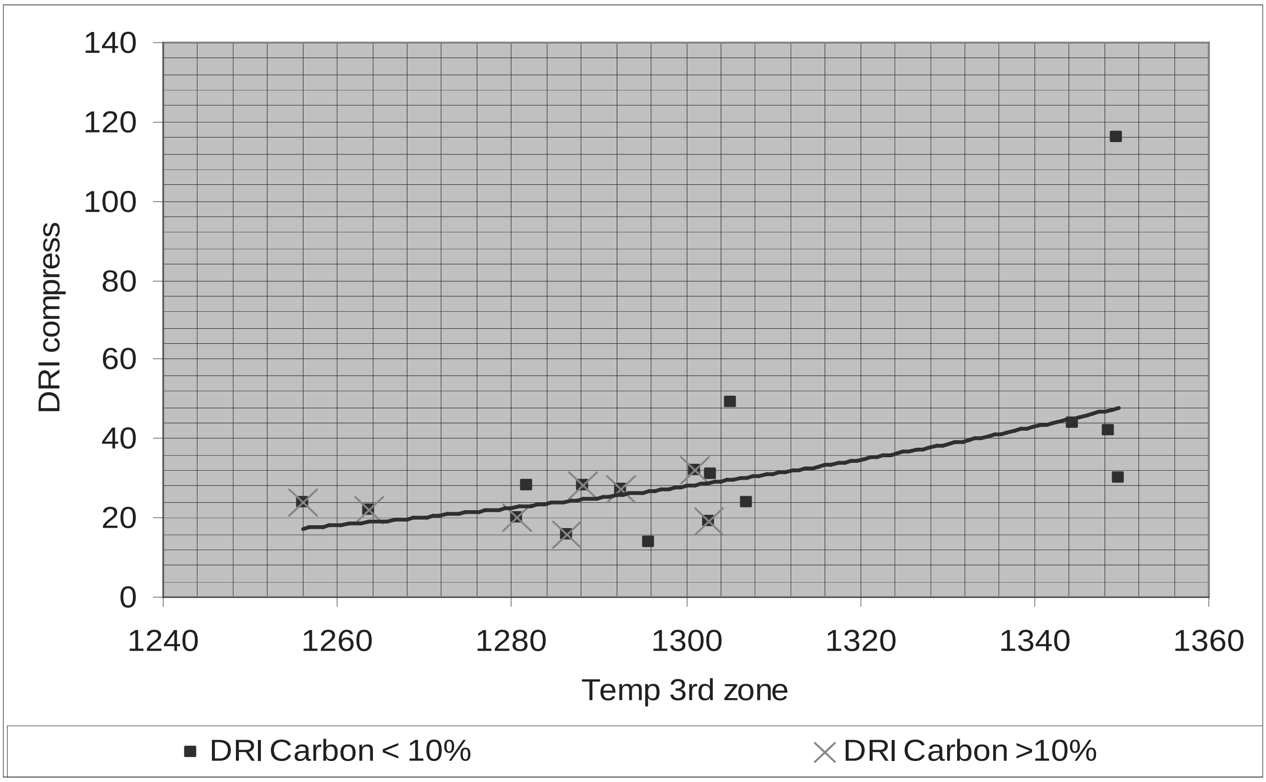


Figure 30. DRI compression strength as a function of 3rd zone temperature

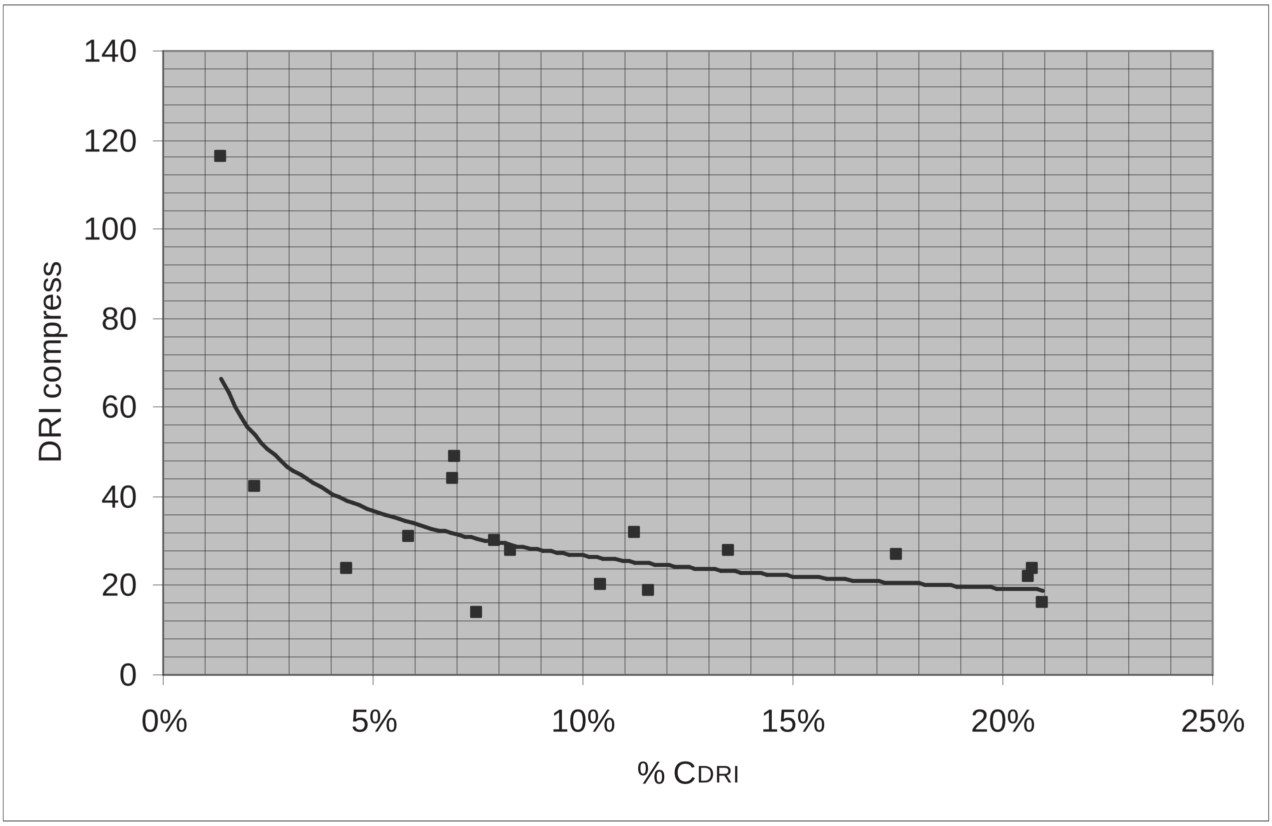


Figure 31. DRI compression strength as a function of carbon content in DRI

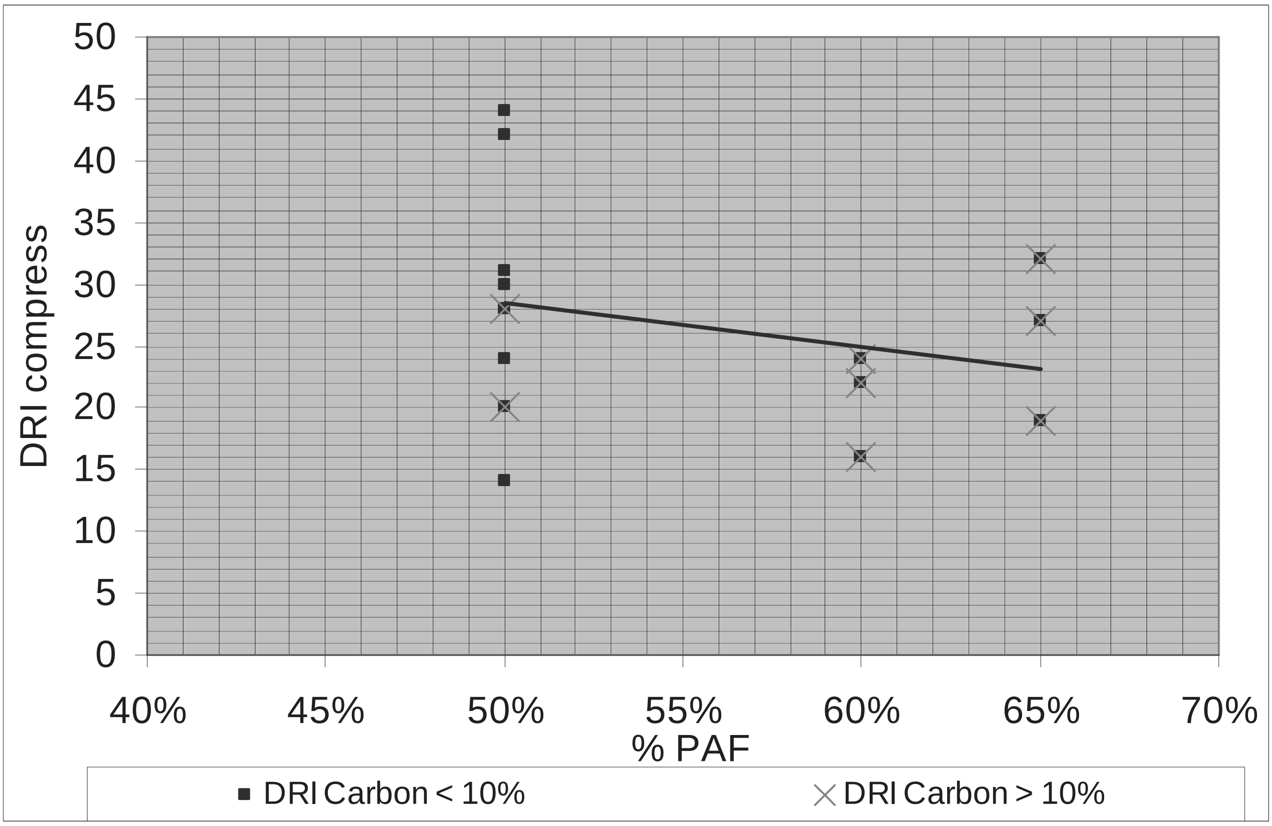


Figure 32. DRI compression strength as a function of percentage of BF dust in charge

MAIN ADVANTAGES RELATED TO THE GREEN PELLETS DRYING

In November 2004 a dryer system for the green pellets was installed between the rotary drum screen and the RHF vibrating feeder.

The dryer was installed to solve the interruptions due to the packing of the vibro-feeder, but has also given some significant advantages: it substantially eliminates the decrepitation phenomena, decreases the RHF fuel consumption and improves the final quality of DRI.

The figures reported in the following show these important benefits related to the dryer (i.e. to a lower amount of water in the green pellets charged into the RHF):

- The RHF total energy consumption decreases when green pellets humidity is lower (Figure 33)
- The RHF fuel consumption decreases when green pellets humidity is lower (Figure 34)
- The reduction degree increases when green pellets humidity is lower (Figure 35)
- The compression strength of DRI increases when green pellets humidity is lower (Figure 36)

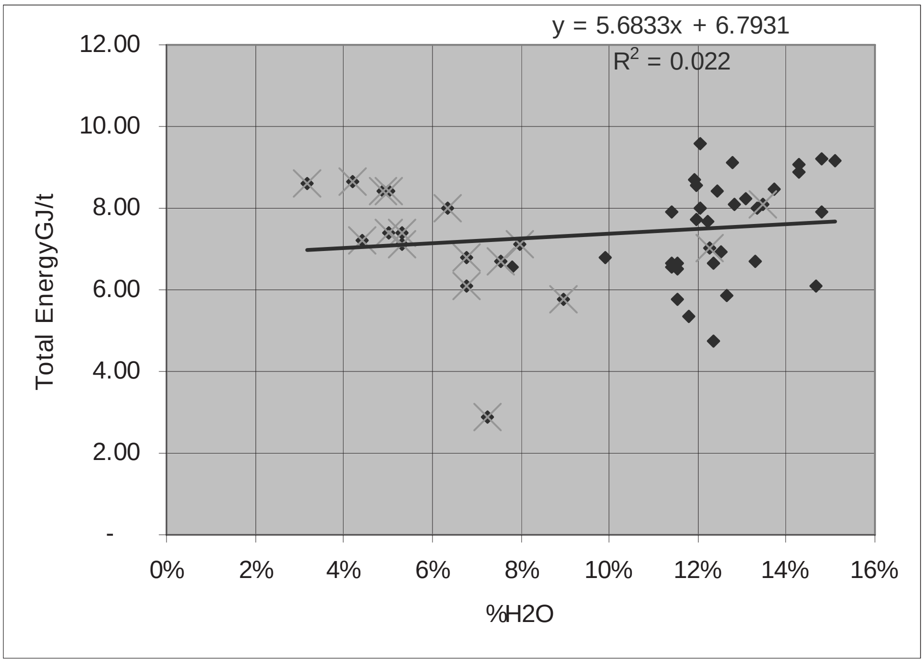


Figure 33. Total energy consumption as a function of green pellets humidity

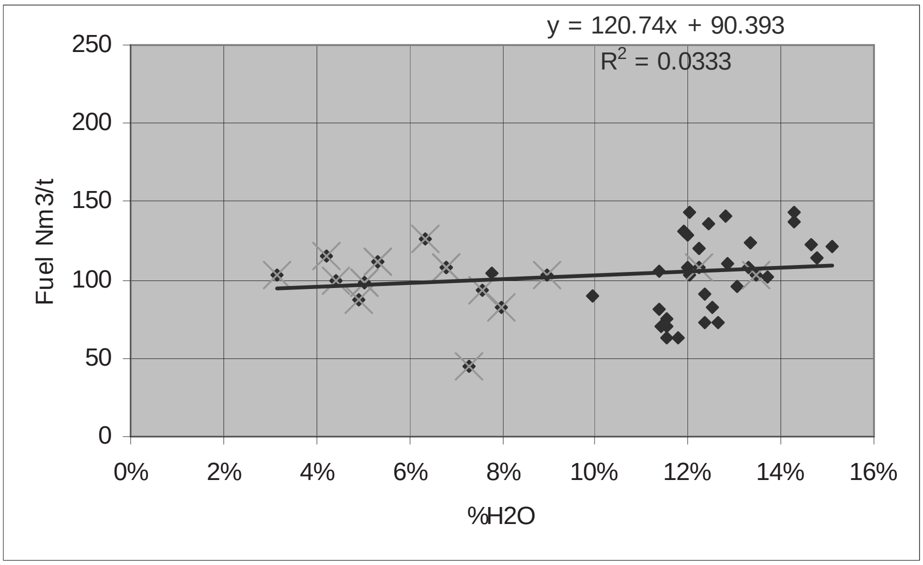


Figure 34. Fuel consumption as a function of green pellets humidity

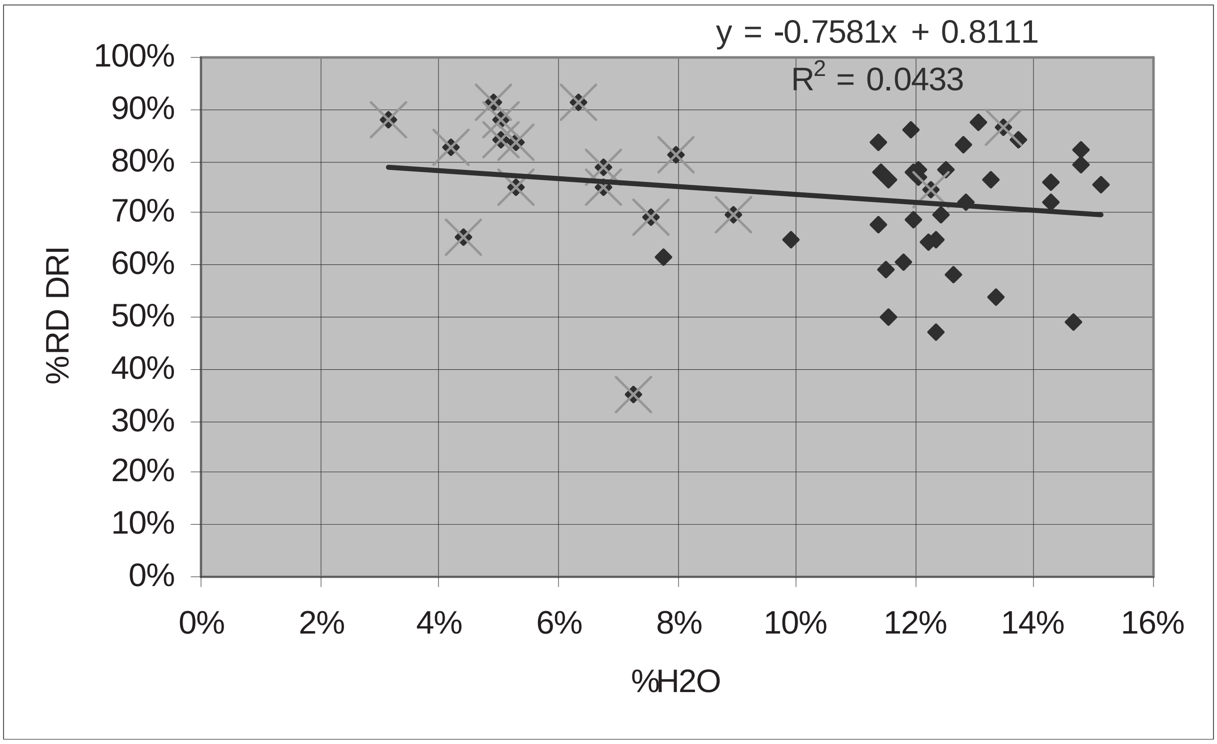


Figure 35. Reduction degree as a function of green pellets humidity

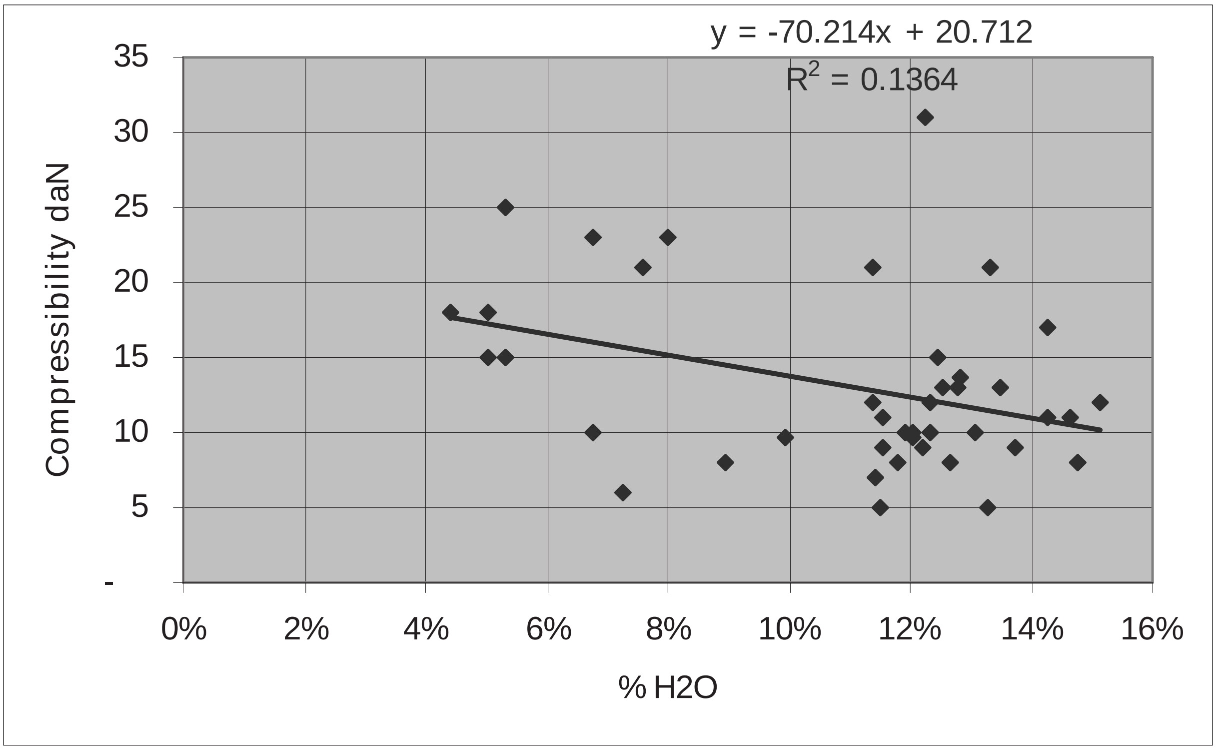


Figure 36. DRI compression strength as a function of green pellets humidity

2.4 Smelter campaigns

In the period between February and December 2004 the following campaigns were carried out for the smelter:

- Hot tests for the smelter unit, using pig iron and cold metallic charge (BF pellets, DRI) to set-up the smelting equipment and the relevant operating practices
- Plant operation of RHF + smelter (tests of short duration), to define the reference configuration of the plant and the reference operating conditions of the global process.

During the trials the following procedures were tested, evaluated and optimised:

- Start-up and shut-down procedure
- Tapping procedures
- Safety operating practices

GUIDELINES

The experimental campaign for testing the smelter process can be subdivided in three main phases. These phases have different objectives: they are in sequence as regards the utilisation of the results and they are tightly connected for the analysis of the achieved information.
The main purposes and the aspects that are investigated in the three phases may be summarised as follows:

1° phase
Check of the components of the plant, in order to verify the correct design, the proper working, the flexibility and the reliability.

Such verification is mainly related to the not-conventional components, specially designed for the plant.

The main components to be tested are:

- Oxy-coal tuyeres (design and materials)
- Post-combustion tuyeres (design and materials)
- Coal and flux injection system
- DRI feeding chute
- Refractory lining
- Siphon tapping system (design and operating procedures)
- Vessel empting system (design and operating procedures)
- Gas analysis instrumentation
- Control system

2° phase
Check the characteristics of the process and the operating practices.

The main aspects considered are the following:

- Melting of cold raw materials, to make the starting liquid metal pool (“hot heel”)
- Keeping liquid bath in a stable state, by appropriate coal and oxygen injection
- Stirring of the liquid bath
- Reduction and melting of cold carbon based DRI
- Reduction and melting of hot carbon based DRI
- Joint management of RHF and smelter for metal production
- Efficiency and control of the reduction of iron oxide in slag by oxy-coal injection
- Efficiency and control of the carburisation of hot metal by oxy-coal injection
- Continuous casting and separation of hot metal and slag
- Control of the waste gas composition by post-combustion oxygen injection

The running and efficiency of the process is mainly function of the following variables:

- Coal injection conditions (flowrate of transport nitrogen and relevant outlet velocity from the nozzle)
- Coal characteristics (quality, composition and size)
- Flow-dynamic conditions of the bath (injected oxygen flowrate, distance between lance and bath surface, slag level)
- Oxidation level of the slag
- Chemical-physical parameters of the system (temperature, density and viscosity of the slag, metal temperature etc.)

3° phase
Analysis and control of the main process parameters, as a function of the operating conditions, and definition of the plant performance.

The main parameters that must be investigated are:

- Efficiency of energy transfer from post-combustion zone to the liquid bath
- Energy transfer of the cooling system
- Coal injection efficiency (carry over)
- Coal and oxygen consumption of the process
- Metal yield (dust formation, iron oxide content in slag etc.)
- Control of hot metal composition (carbon level, de-sulphurisation, de-phosphorisation, silicon content etc.)
- Maximum productivity
- Operating consumption (refractory, utilities etc.)

The evaluation of the plant performance needs tests of long duration (at least some days in stable conditions).

RESULTS

The main outcome obtained during the experimental campaigns carried out in 2004 is summarised below.
The results of the work accomplished are organised according to the different objectives that were fixed during the development of test campaigns.

Objective: Formation of the starting liquid pool (mainly by using the oxy-fuel burner)

The possibility of forming a liquid pool, starting from granulated pig iron, has been proven.
The hot heel is formed by melting pig iron charged from the top.
These additives are charged during the start-up:

- Lime to control the basicity of the slag
- Coke (size < 30 mm) to control the carbon content of the hot metal
- Fe-Si to control the oxidation degree of the slag

The oxy-fuel burner shows a good flexibility, even if with a low efficiency (which was in any case expected, especially due to the fact that it is installed on the roof of the vessel)

During the empting of the vessel carried out through the bottom tap hole at the end of each campaign, it may happen that some solid pig iron and slag remain on the bottom part of the smelter.
For this reason after the first campaign it was necessary to investigate the possibility of melting solid pig iron, left on the bottom part of the vessel. It was verified that in this case the starting phase of the melting requires more time: the residual pig iron can be melted during the start-up phase, but only when stable thermal conditions are reached.

After the first campaigns it was then defined a new starting procedure, to increase the velocity of formation of the starting liquid pool. Just a limited amount of granulated pig iron was melted by the oxy-fuel burner and the starting liquid pool was formed mainly by using the oxy-coal lances. This start-up procedure is very fast, if compared with the one made just by the oxy-fuel burner. Granulated pig iron and coke in small size have been charged and, in less than three hours, inside the vessel there was a liquid bath high enough to utilise the measuring probes and to take samples.

Objective: Metallurgical control of conditions inside the smelter

Since the first campaigns it was verified that the thermal conditions of the liquid bath could be controlled, by measuring its temperature and adjusting the fuel rate (natural gas of the oxy-fuel burner or coal injected through the lances).
It was also clear from the beginning that the continuous control of the composition and oxidation of the slag/metal was a fundamental practise, to improve the control and the performance of the process.

According to the initial operating practices the samples should have been taken directly in the siphon. But soon after the first campaign it was clear that, in order to have a control of the process, it was necessary to take samples directly inside the smelter. This is mainly related to two important considerations:

- Many hours are necessary before the products reach the level of the siphon hole and it’s not reasonable to be “blind” on process conditions for such a long period
- The process evolution is extremely dynamic and the only way to have a metallurgical control of the process is to monitor the slag and metal conditions inside the vessel.

This took to the decision of taking out temporarily one of the three oxy-coal lances (which are in any case over-sized for the nominal coal flow-rate), in order to create an inspection hole, to see and check the physical-chemical conditions of the liquid bath. Through this hole, plugged by refractory during normal operation, it was possible to take samples and to monitor the bath level.
During the first campaigns the inspection hole showed one significant limitation: the foaming slag formed during the process obstructed the hole and after some hours of operation it was not possible anymore to open it and take samples.
For this reason it was necessary to install a water-cooled pipe in correspondence of the inspection hole. This solution prevented the occlusion caused by the foaming slag: the hole could be cleaned with a suitable tool and then could be utilised during the whole trial. In such a way it was possible to take samples and to introduce the measuring probes.
(During the stoppage made in November 2004 the third oxy-coal lance was re-installed and the final inspection hole was built in the vessel shell).

After the first tests it was clear that the temperature measurement system was working in an acceptable way, but the instrument to measure carbon and silicon was not adequate at all for this particular process, at least during the start-up phase, when the level of liquid products inside the smelter are very low.
Taking samples of liquid metal was not always so easy, especially due to the small amount of liquid metal (low level) and the measurement of C in the metal was impossible during the whole start-up phase.
It was then necessary to have an instrument capable of overcoming this problem. The best solution seemed to be the utilisation of a multi-probe system with the direct acquisition of the following main parameters: temperature, oxygen activity in liquid metal, iron oxide content in the slag and carbon content.

Before taking a final decision regarding the equipment to be installed, several tests were performed with an instrument for the on-line measurement of metallurgical parameters.
This equipment, by means of special probes, allowed measuring the following process parameters:

- % FeO in slag (i.e. the oxidation degree of the slag)
- Oxygen activity of the liquid metal (corresponding to the oxidation degree of metal)
- % C in metal (evaluating the re-carburisation of the metal)
- Temperature of slag and liquid metal (controlling the thermal state of the bath)

The values obtained during the testing period were compared with the ones coming from the chemical laboratory of Blast Furnace Plant and the results showed a satisfying agreement. It was also verified that FeO in slag and metal carburisation are correlated each other very closely and consequently the slag FeO measurement (by O activity probe) could be elected as key indication to control the process.
This equipment was considered suitable for the on-line metallurgical control of the process and it was therefore installed on the plant.
During the following campaigns it was confirmed that the parameters measured by this instrumentation system were sufficient to control the metallurgical trend of the process.

Another complication for the metallurgical control in real time is due to the high rate of reaction occurring in the process.
This fact is mainly consequence of the following two factors:

- The turbulence of the system, which does not permit to reach stable conditions for the measurements
- The non-equilibrium situation, involving a large difference between the oxidation degree of slag and metal and gradients of oxygen potential also inside the same phase

To solve at least partially this problem, the samples must be taken suspending the coal injection (to reduce turbulence conditions).

Objective: Check the main auxiliary components and the operating procedures:

- Water cooled components (copper stripes, cooled roof and cooled duct)
- Batch feeding system installed on the water cooled roof
- Tapping from the bottom drain hole

The main components have shown a satisfying behaviour

- The cooling water temperature increase has not exceeded 10 °C in any condition
- The top charging system (used for the batch charging of pig iron, coke, lime and other additives) is properly designed and always guarantee satisfying operation
- The final drain of the smelter, at the end of a test campaign, is made through a bottom drain hole. Despite of the limited space available, the operation of this taphole has always been satisfactory.
  The operating practice defined for the first campaign was confirmed and no modifications were needed.
  Picture 3 shows the first tapping through the bottom drain hole.

Objective: Monitor the behaviour of refractory lining

The refractory lining used in the critical slag area (in correspondence of and below the copper stripes) has shown a very poor resistance since the first phases of testing.

After the completion of the first heating of the smelter a significant problem to the refractory was already encountered: the special bricks used in the cooling stripes area were completely damaged (Picture 4). Due to this problem it was necessary to postpone the first smelting.

To analyse the causes of the damage suffered by the refractory, a stress thermal analysis of refractory bricks was performed using ANSYS (the study is reported at paragraph 2.6.3).
Two basic conclusions were given y the study:

- The design of the brick was not adequate to the heavy conditions to which it was exposed during the operation (i.e. very high temperatures on the hot face of the brick and very high temperature gradient between the hot side and the inner surface in contact with the cooled copper stripe). Due to its geometry and size, the brick was in fact subject to stresses that are not compatible with the mechanical characteristics of the refractory material.
- The very low thickness of the expansion joints left between the bricks was not sufficient and strongly contributed to increase the stresses on the bricks

To solve the problem of the damaged refractory, it was therefore necessary to design a new brick and to define a different erection procedure (a higher thickness for the expansion joints).

Picture 3 The first casting through the drain bottom hole

Picture 4 Cooling stripes area: the damaged refractory below an oxygen lance

The smelter refractory was in bad conditions, but a reconstruction of the smelter (considering the overall time required for supply, demolishing and erection), would have taken between three and six months, with a consistent delay in the programme of activities.
It was decided therefore to go on with the test programme, with a careful monitoring of the refractory status. The new refractory bricks would have been installed during the stoppage foreseen for the erection of the green pellets system: the intervention would have been anticipated only if essential.

During the firs campaigns the refractory lining was subject to further erosion.
It must be noted that erosion phenomena were expected. This behaviour was analysed and studied by a CFD calculation, which was carried out at the very beginning of the project, for the design of the water-cooled copper elements. The goal of the cooling system in the critical slag area was in fact to generate a frozen layer of slag in front of the refractory lining, in order to stop any further wear.

Nevertheless it was considered more careful to make some interventions of refurbishing.
At first a high alumina castable was tested, but during the operation this refractory did not resist to the process conditions and caused the formation of a slag with a very high percentage of alumina.
This slag had a very high viscosity and then the jet penetration of the oxygen was limited, decreasing its efficiency and causing the oxy-coal lances to be not effective during the trial.

Another testing was carried out with a tixotropic refractory lining (composed by alumina, silicon carbide and graphite). The tixotropic refractory lining showed to be totally unsuitable for the operating conditions of the smelter. The strongly oxidizing conditions occurring during the formation of the hot heel, due to the utilisation of the oxy-fuel burner, caused the erosion of carbonaceous structure of the refractory and the subsequent melting of the alumina.
The phenomenon of erosion of the refractory lining, already observed during the previous trial, increased, due to the choice of a carbon based material. The slag with a very high content of alumina made the oxy-coal blowing completely ineffective and the thermal and metallurgical control of the process was precluded.

After these unsuccessful trials, the partners decided to leave the copper stripes area just with the original refractory lining, even if highly damaged, without any additional protection.
With this operation the possibility of working with a “freezing line” condition was confirmed (Picture 5 shows the slag lining formed during operation).
A new material (alumina-chromite castable) was tested in the slag/metal line, the working area in the heaviest conditions. The performance was very good and its condition was still satisfying when the smelter was stopped for relining in November 2004.

Especially in the last campaigns (second semester 2004) the copper stripes worked essentially without any refractory. They worked just with the frozen slag lining formed during the operation.
The evidence of this behaviour was that during the pre-heating with the oxy-fuel burner the temperature on the copper stripes increased very quickly (due the to falling of the previous slag build-up) and when the coal injection system was activated the copper stripes were quickly cooled (due to the formation of a new slag build-up). Also the use of high post-combustion rates caused some temporary problems for the slag lining of the copper stripes (sudden falling and quick reformation of the slag lining, with a temporary significant increase in copper temperature).
During the campaigns performed with “bare” copper stripes, the most difficult issue was to keep the bath inside the smelter hot. The efficiency of the copper cooling system was, in fact, too high and it was sufficient to suspend the coal injection for a short time, to cause a drastic decrease in bath temperature.
The operation in these conditions was extremely difficult, also because a short suspension of the coal injection was required more or less once an hour, to take samples and control the process conditions.

During the stoppage made in November 2004 the smelter refractory was completely rebuilt (using the new concept brick and the same refractory material).

The performance given by the new refractory unfortunately was not satisfying and the partners are convinced that the bad behaviour was caused by the low quality of the bricks (not all the requested characteristics were respected during the preparation of the bricks).
It was therefore decided to replace the damaged refractory with a castable of the same type, but supplied by another refractory company. The first results seem encouraging (the status of the refractory after one test campaign are excellent), but they must be confirmed with longer operation.

Picture 5 The slag lining formed during operation

Objective: Check the operating conditions with the oxy-coal lances in operation

In the first test campaigns the oxy-coal lances operated continuously and in stable conditions and they showed the capability of reaching a coal flowrate of much more than 1000 kg/h (nominal design value).
The values of coal flowrate, as a function of injection pressure, matched with the values measured during the cold test. The result of the first campaigns was that the coal flowrate could be adjusted in a very precise way by regulating the injection pressure, the lances could work with a large range of ratios of coal and oxygen and could operate with flexibility and regularity.
The only (minor) inconvenience was the impossibility to have a reliable value of coal flowrate during the periods in which the pressure tank was charged. This is due to the fact that the quantity of injected coal is calculated by a loss in weight system, i.e. on the basis of the weight of coal inside the pressure tank, but the weight value has instability during the batch periodic charging of the pressure tank.

During the first tests it was observed that the slag turbulence influenced the efficiency of the oxy-coal lances. To overcome this limitation, the oxy-coal lances were installed inside the refractory, to increase the distance between the lance tip and the slag surface.
Under these working conditions it was observed that the new position of the lances had practically prevented the reaction of the oxygen with the injected coal.

The oxygen escaped, without producing CO or CO2, and to continue the operation it was necessary to take back the lances in the former position.

During the operation by using the oxy-coal lances it was also possible to evaluate the velocity of heating and melting. Stable running conditions were reached and a simplified mass and energy balance was carried out for matching the operating data.

The preliminary analysis of the data shows a velocity of melting of about 600 kg/h with an oxygen injection of about 200 Nm^3/h. This value corresponds to the melting capacity of 3000 kg/h with 1000 Nm^3/h, foreseen for the hot DRI. In any case, the blowing, carried out in oxidizing conditions, caused the oxidation of the slag and the de-carburisation of the liquid metal.
The oxygen blowing, also with relatively low rate, showed the formation of an emulsion formed by slag, gas and a small amount of liquid metal. The emulsion, as well known, is a fundamental factor to increase the kinetic of the reaction and the energy transfer from the post-combustion zone to the reaction zone. On the other hand, in this condition it was very difficult to take significant samples: it was necessary to define an operating practice requiring that the oxy-coal injection was suspended to take the samples.

During the last campaigns (second semester of 2004) unfortunately the coal injection system showed a high degradation of its performances:
- Difficult control of the coal dosing from the pressure tank to the feeding lines
- Frequent temporary blockage of the valves between the pressure tank and the feeding lines

These anomalies cause a limited operability range and a wide uncontrolled fluctuation of the coal flowrate.

The regular performance of the pneumatic coal injection is a key pre-condition to carry out any smelter tests, so several changes were introduced to the coal feeding and transportation system.
As a result, the system performance and stability of operation have improved, even if this remains the main cause of unplanned delays during tests.

A new design of the oxy-coal lances has been studied: the new lances will be installed in April 2005.

Objective: Analysis of the working conditions with high post-combustion

The post-combustion lances have always operated in a regular way and have shown their reliability

During the first tests the lances could be tested at a sufficient rate only for very short periods, due to a limitation of suction capacity of the waste gas system. The off-gases coming from RHF and from the smelter, in fact, use a common suction system and some difficulty was found to balance the pressures of the two units. The problem was fixed by a small design change of the RHF off-gas duct.

The increase of post-combustion oxygen has shown a correspondent increase of reaction rate of the whole reduction process, with a rise of CO or CO_2 content in the fumes.
The intensive use of post-combustion lances has confirmed, even if for short periods of operation, the increase of the global efficiency of the oxygen reaction.
The oxidation level of slag (and consequently of metal) can be controlled, by injecting coal and oxygen in a suitable ratio. After continuous oxygen blowing of about 8 hours, the carbon content of the metal was higher than 3 %, without any direct re-carburisation.

Objective: Tapping through the siphon

During the first campaigns an operating practice was defined to make the tapping of slag and metal through the siphon.
The procedure worked in a successful way and the following points seemed proved:

- The slag tapping was very easy
- The tapping hole remained free (the slag had a temperature high enough)
- It was possible to proceed with charging during the tapping
- It was possible to continue the oxy-coal injection during the tapping

The slag evacuated was more than 1000 kg, without any phenomenon of freezing or plugging (Picture 6 shows the first tapping through the siphon).

Picture 6 The first casting through the siphon

Unfortunately different results were obtained for longer periods of operation, mainly due to the quality of the slag: even with a short period of a more viscous slag (different basicity or lower temperature), the slag froze in the refractory block between the vessel and the siphon. In these cases it was necessary to stop the hot DRI charging, because it was not possible to evacuate the products.

This problem is mainly related to the big thermal capacity of the tapping siphon, which makes difficult to keep the hot metal and the slag in the liquid state. As a modification to the siphon would have taken to a drastic intervention, it was decided to simplify the tapping system and tap metal and slag on a batch basis.

Objective: Melting tests of different cold materials

A charge of iron ore pellets (blast furnace pellets, about 500 kg) was melted very quickly.
The significant formation of CO (due to the presence of iron oxide) caused a slopping phenomenon, which did not permit to reach stable conditions and to verify the velocity of reduction.

The test of melting and reduction of cold DRI previously produced by the RHF was successful.
The pellets were highly oxidised (for the direct exposition to the atmosphere oxygen during the cooling) and with a large quantity of fines.
The melting of the pellets was very quick, soon after the contact with the bath surface and there was formation of CO bubbles, which lowered the density of slag, increasing the level of the liquid bath.

The control of the atmosphere composition inside the smelter could be easily reached and the response time of the analyser was a few minutes.
The CO production, during the process, influences the physical characteristics of the slag, as well known. Feeding a large quantity of oxidised DRI requires the control of the waste gas composition to prevent possible slopping phenomena.

Objective: Joint management of the RHF and smelter for the direct charging of hot DRI and relevant test of melting and reduction

The connection of the RHF and the smelter was always carried out with success, except for the first time in which it was tested. In that case, in fact, the DRI pellets discharged at very high temperature melted very quickly, but a mechanical problem concerning the rotation of the feeding chute did not permit to extend the test for a longer period.
The first joint test of RHF and smelter in any case confirmed the consistence of the design choices and the feasibility of the process was demonstrated, even for a short time.

During the next campaigns the connection between RHF and smelter was normally stopped for two main reasons:
- Instability of the coal injection system, that did not permit a proper control of the melting
- Freezing of the slag in the tapping siphon, with the impossibility of evacuating the products

The DRI feeding chute, which is a not conventional equipment, has always worked regularly and has shown its reliability.

The DRI melting is never a problem, when sufficient turbulence is maintained inside the vessel. In some conditions when DRI did not start melting, some more oxygen was injected with the coal and the process conditions dramatically changed, causing a very quick melting of DRI.

Re-carburisation of liquid metal formed by coal-based DRI cannot be considered fully proved, because the time available for hot DRI continuous charging has always been too limited and stable conditions were not reached.

During the development of the test campaigns the control system software has been suitably improved, taking into account the operators requirements and now it can be considered satisfying.

For each campaign mass-energy balances have been carried out, on the basis of the operating data collected during the periods in which stable conditions were reached. Table 4 shows an example of this balance, made starting from a reference condition of the 9th campaign.

OPERATING DATA
of
9° EXPERIMENTAL TRIAL

MELTING OF COAL-BASED DRI (stable conditions)

MAIN PARAMETERS

Oxygen flowrate	350	Nm3/h
Coal flowrate	406	kg/h
Post-combustion oxygen flowrate	124	Nm3/h
Nitrogen flowrate	120	Nm3/h
Average waste gas composition (from analyser)		
CO	11.8	% vol
CO2	27.1	% vol
O2	5	% vol
H2	0.3	% vol
N2	55.8	% vol
Staves water flowrate	144	m3/h
Staves water temperature difference (avg)	1.8	°C
Roof water flowrate	120	m3/h
Roff water temperature difference (avg)	2.6	°C
Steady state reference period	65	min

ENERGY BALANCE

Reaction zone

Energy from reactions	6095	MJ
Enthalpy of existing materials (evaluated)	1405	MJ
Energy from post-combustion (from air entrance)	1036	MJ
Enthalpy of metal+slag	2479	MJ
Enthalpy of waste gas	3065	MJ
Losses	1282	MJ
Unbalanced energy (due to unsteady condition)	1710	MJ

Post-combustion zone

Energy from gas reactions	3065	MJ
Energy from post-combustion	4144	MJ
Enthalpy of waste gas	5700	MJ
Losses	1509	MJ

Table 4. Smelter mass/energy balance – Stable conditions – 9th campaign

CONCLUSIONS

Even if the new technology is not ready yet for the industrial exploitation, it is believed that the results obtained during the tests of short duration have substantially proved the technical feasibility of the process. Most characteristics of the process have been verified and proven. Even if some of the data collected and/or analysed during the tests of short duration can already be considered significant, the evaluation of the performance of the process must be done with longer periods of operation in stable conditions.

The tests of long duration could not be carried out within the end of the project, because some key components of the smelter could not reach satisfactory performances even during tests of short duration (few shifts). The following problems were still pending during the last campaign carried out in December, even if the solutions had already been identified:

- Due to the critical slag conditions, especially during the transient periods when big fluctuations in FeO content may happen, the refractory lining in the slag area showed a quick erosion rate. To solve this problem a new refractory (castable type) was identified.
- Due to the big thermal capacity of the tapping siphon, it was difficult to keep the hot metal and the slag in the liquid state. To solve this problem it was decided to simplify the tapping system and tap metal and slag on a batch basis.
- The coal injection system showed a number of problems, which caused a limited operability range. Several changes were introduced to the system and some improvements could be reached, but the instability of coal injection remained the main cause of unplanned delays during tests. To further improve the coal injection performances a new type of oxy-coal lance was designed.

The tests of long duration planned in 2005 should give conclusive results regarding the process consumptions (coal, oxygen and also minor utilities), but as regards the refractory consumption it is thought that they will give just an indication of which refractory types may be considered for the commercial unit (discarding the ones that have demonstrated to be inadequate to the critical conditions present in the slag area of the smelter). The actual refractory consumption may be verified only after some months of operation (some days are not sufficient) and for this reason the confirmation of this consumption figure must be postponed to the next step of the development of the new technology.

2.5 Emissions

Emissions have been measured during some significant periods of the tests campaigns.

The following measurements have been carried out:

- DRI production (RHF in operation), sample taken at the inlet point of dedusting bag filter (Table 5)
- Hot metal production (RHF + smelter in operation), sample taken at the inlet point of dedusting bag filter (Table 6)
- DRI production (RHF in operation), sample taken at the stack, after dedusting bag filter (Table 7)

At the current stage the reference data for the plant emissions can be summarised as follow:

Dusts	604,10 mg/Nm^3
Sb	0,0024 mg/Nm^3
As	< 0,002 mg/Nm^3
Cd	0,0297 mg/Nm^3
Cr	0,0284 mg/Nm^3
Fe	5,3514 mg/Nm^3
Mn	0,1935 mg/Nm^3
Ni	0,0046 mg/Nm^3
Pb	2,3311 mg/Nm^3
Cu	0,0346 mg/Nm^3
Zn	13,205 mg/Nm^3

Table 5. RHF emissions (before dedusting)

Dusts	802,06 mg/Nm^3
Sb	0,0212 mg/Nm^3
As	< 0,002 mg/Nm^3
Cd	0,1314 mg/Nm^3
Cr	0,2791 mg/Nm^3
Fe	17,143 mg/Nm^3
Mn	1,5392 mg/Nm^3
Ni	0,0130 mg/Nm^3
Pb	4,0188 mg/Nm^3
Cu	0,0762 mg/Nm^3
Zn	48,781 mg/Nm^3

Table 6. RHF +smelter emissions (before dedusting)

Dusts	1,81 mg/Nm^3
Sb	< 0,002 mg/Nm^3
As	< 0,002 mg/Nm^3
Cd	< 0,002 mg/Nm^3
Cr	0,0038 mg/Nm^3
Fe	0,0861 mg/Nm^3
Mn	0,0031 mg/Nm^3
Ni	< 0,002 mg/Nm^3
Pb	0,0071 mg/Nm^3
Cu	< 0,002 mg/Nm^3
Zn	0,0528 mg/Nm^3
SO_x	3,5 mg/Nm^3
NO_x	2,5 mg/Nm^3

Table 7. RHF emissions (stack, after dedusting)

The emissions values measured during the tests campaigns are very low (even lower than expected). Other measurement campaigns are foreseen during the tests of long duration, with both units in operation, to verify and confirm the values that until now have been registered.

2.6 Modelling

During the development of the project different models have been developed:

- CFD models for the optimisation of the RHF design.
  Even though the RHF is based on an existing technology, the special requirements of this application were taken into account and many details were analysed using advanced software tools. In particular the following studies were performed:
  - CFD study to identify the best arrangement and geometry of the combustion equipment (burners, air wickets, gas wickets, etc), paragraph 2.6.1
  - CFD study to verify the design of the DRI discharging screw, paragraph 2.6.2

- After the completion of the first heating of the smelter a significant problem to the refractory was encountered: the special bricks used in the cooling stripes area were completely damaged. To analyse the causes of the damage suffered by the refractory, a stress thermal analysis of refractory bricks was performed using ANSYS (paragraph 2.6.3). In particular two main factors were studied: the design of the brick and the methodology used during erection. The study proved that the original design of the brick was not adequate to the actual operating conditions of the smelter. A new brick was designed (and verified) and it was installed during the stoppage planned for the erection of the green pellets drying system.

- Data collected during different campaigns have been used to carry out, for each significant test, two different types of material and energy balance, implemented in 1-D model (paragraph 2.6.4) and supported by CFD simulations implemented by 3D fluid-dynamic simulation tool (paragraph 2.6.5), in order to define and set the parameters relevant to the RHF direct reduction process.
  The “1-D” model program carries out one-dimensional thermal calculation along the furnace length, aiming at analysing on a local basis the parameters of the reduction process and to simulate alternative operating conditions.
  The 3D CFD model is used to make three-dimensional simulations, in order to tune the 1-D model and to characterise the fluid-dynamics of burners and air/gas wickets.

2.6.1 CFD study to optimise RHF combustion system

The design of the Rotary Hearth Furnace for the LUCCHINI-Piombino demonstration unit is mainly based on the know-how available in SMS Demag for this type of units. In particular, SMS Demag is licensee of the Inmetco™ RHF technology as applied to metallic waste treatment. During the last few years, SMS Demag has further developed and engineered this technology in many components.

The pre-reduction process taking place in the RHF is a key factor of the new Redsmelt NST ironmaking route. High metallisation, constant C/O ratio, good mechanical strength, little scatter of all these DRI properties are top important factors to allow a stable smelting process and eventually result in a successful demonstration. In addition, low fuel consumption, long refractory lifetime, little dust carry-over are necessary to make the new route economically competitive.

For these reasons, the Project partners have decided to introduce advanced CFD methods in the design stage of the RHF. This report summarises the results of this optimisation study. The same CFD model, after suitable tuning, has been also utilised during the test phase for supporting the theoretical analysis with the experimental results.

Main targets of the RHF design optimisation are:

- to maximise the heat exchange efficiency between the furnace chamber and the bed
- uniform cross distribution of the heat flux to the bed
- minimum gas velocity above the bed to avoid dust carry-over
- no free oxygen at the bed level, with CO/CO2 ratio as high as possible, to avoid Fe reoxidation
- Minimum residual CO in the off-gas (i.e. maximum CO post-combustion within the furnace)
- Minimum temperature peaks at the inner refractory surface to avoid attack to refractory due to melting of FeO or other dust low-melting components
- Correct pressure distribution across the furnace, to prevent gas backflows and excessive air ingress from the charging/discharging doors

The fluid-dynamic analysis has been carried out using the “FLUENT” software. The CFD model covers only the furnace chamber and considers the bed material as a boundary condition. Another mathematical model is used to predict the chemical processes taking place in the bed and supply the boundary conditions to the CFD model. Of course, the two models must be utilised in a recursive way to take into due account the cross-influences.

Nevertheless, for the RHF design optimisation, the direct comparison of CFD results from different design configurations is sufficient to select the best solution, using a fixed boundary condition at the bed surface. This is the procedure that has been followed to carry out this work.

The CFD model consists of about 400,000 computational cells. Figure 37 and Figure 38below show the overall furnace geometry and some details of the burners.

In particular, the CFD study aimed at determining the following design features:

- Burner type: size and geometry of the gas and air nozzles (influencing the flame length, the temperature profile, the gas turbulence etc.)
- Number, location and orientation of the burners
- Number, size, location and orientation of air wickets
- Number, size, location and orientation of gas wickets for possible “flameless” combustion

Each furnace zone has different process conditions and requirements, and therefore the optimisation work must be carried out using different criteria for each of them. Of course, any change in a zone influences also the other ones and very often the cross-interactions of single changes are very far from the simple addition of the separate effects. For these reasons, any change requires to be simulated over the entire RHF model and checked in many combinations with other variable parameters.

This gave a very large number of CFD simulations (about 50) and a very complex analysis of their results. As an example of this study, here are some results related to two important RHF features.

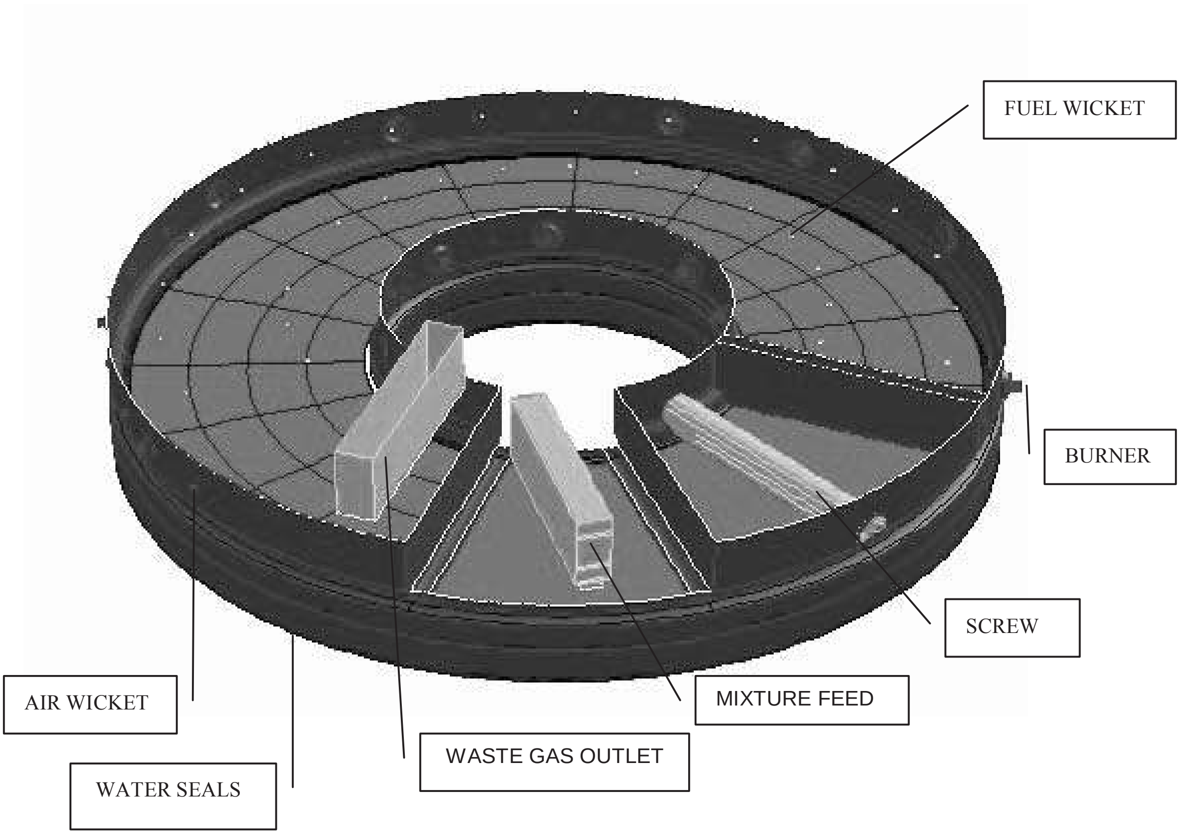
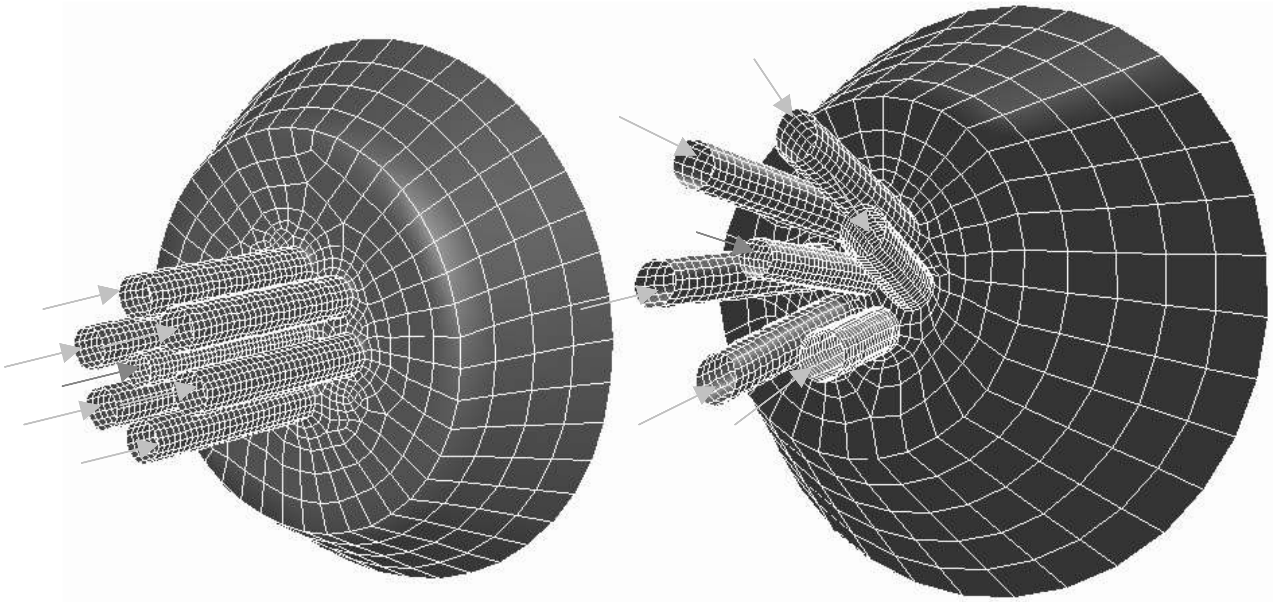


Figure 37. CFD model – overall furnace geometry



a) Burner without swirl b) Burner air swirled

Figure 38. Burners geometry and grid detail

BURNER POSITION

The CFD analysis allows evaluating the interference among the flames and the consequent heat flux distribution to the bed.
In Figure 39 an example is given regarding the effect of different burner locations in furnace zone 3 (the last one). The resulting heat flux and the cross-influence with other furnace zones are shown. The preferred solution is that marked as “Rev1”.

Fig. a: Temperature distribution over a horizontal plane 650 mm from the bed (colour scale: 920 –1400 °C)	Fig. b: Heat flux distribution to the bed (colour scale: 10 - 130 kW / m^2)

REFERENCE GEOMETRY

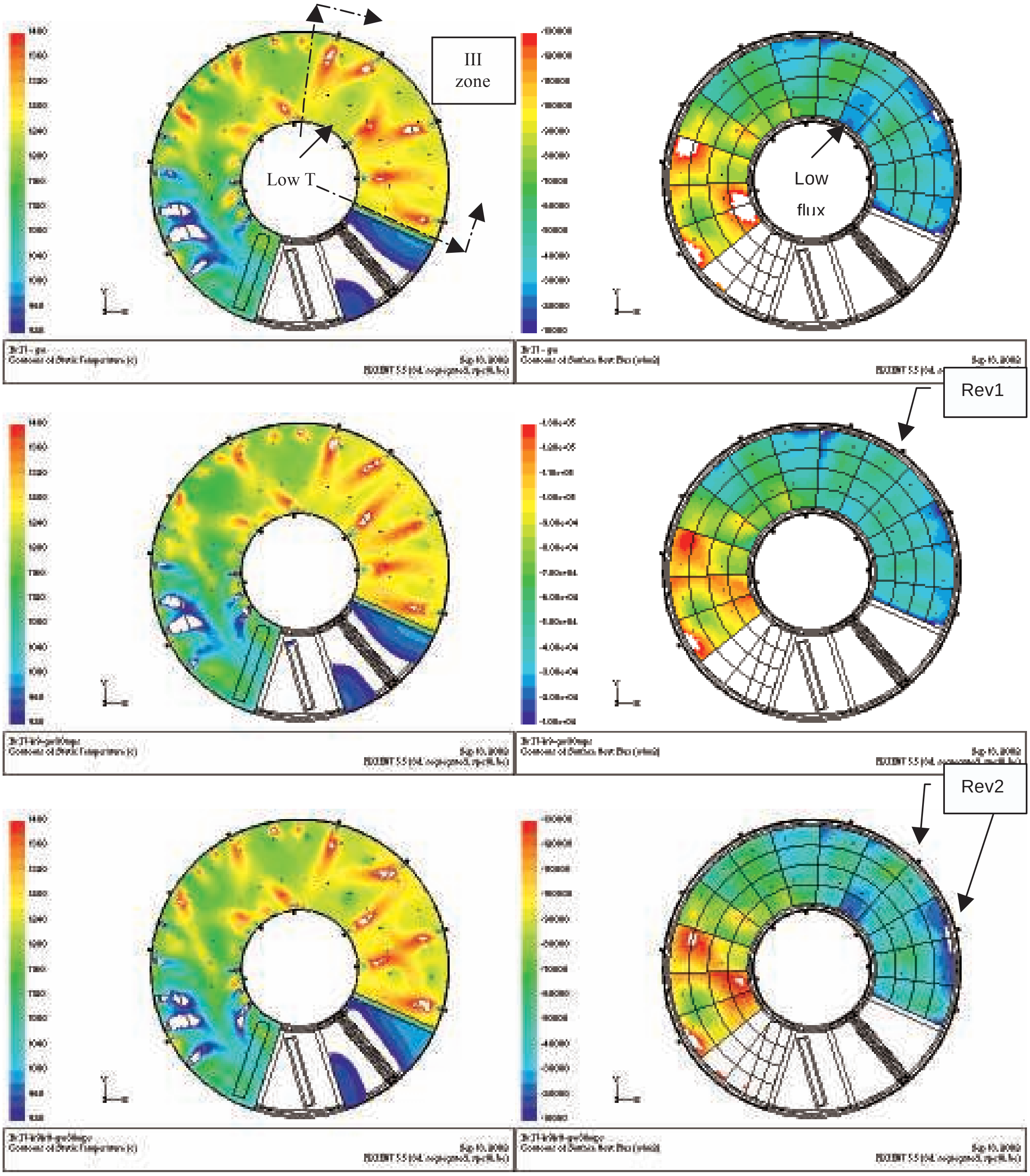


Figure 39. Burners location

AIR WICKET AND BURNER SLOPE

Different solutions have been tested. This example shows a different effect of slope onto the three zones. In the first zone the highest heat flux is obtained with upward nozzles while in the third zone with downward nozzles are more efficient (Figure 40).

Fig. a: Temperature distribution over a horizontal plane 650 mm from the bed (colour scale: 920 –1400 °C)	Fig. b: Heat flux distribution to the bed (colour scale: 10 - 130 kW / m2)

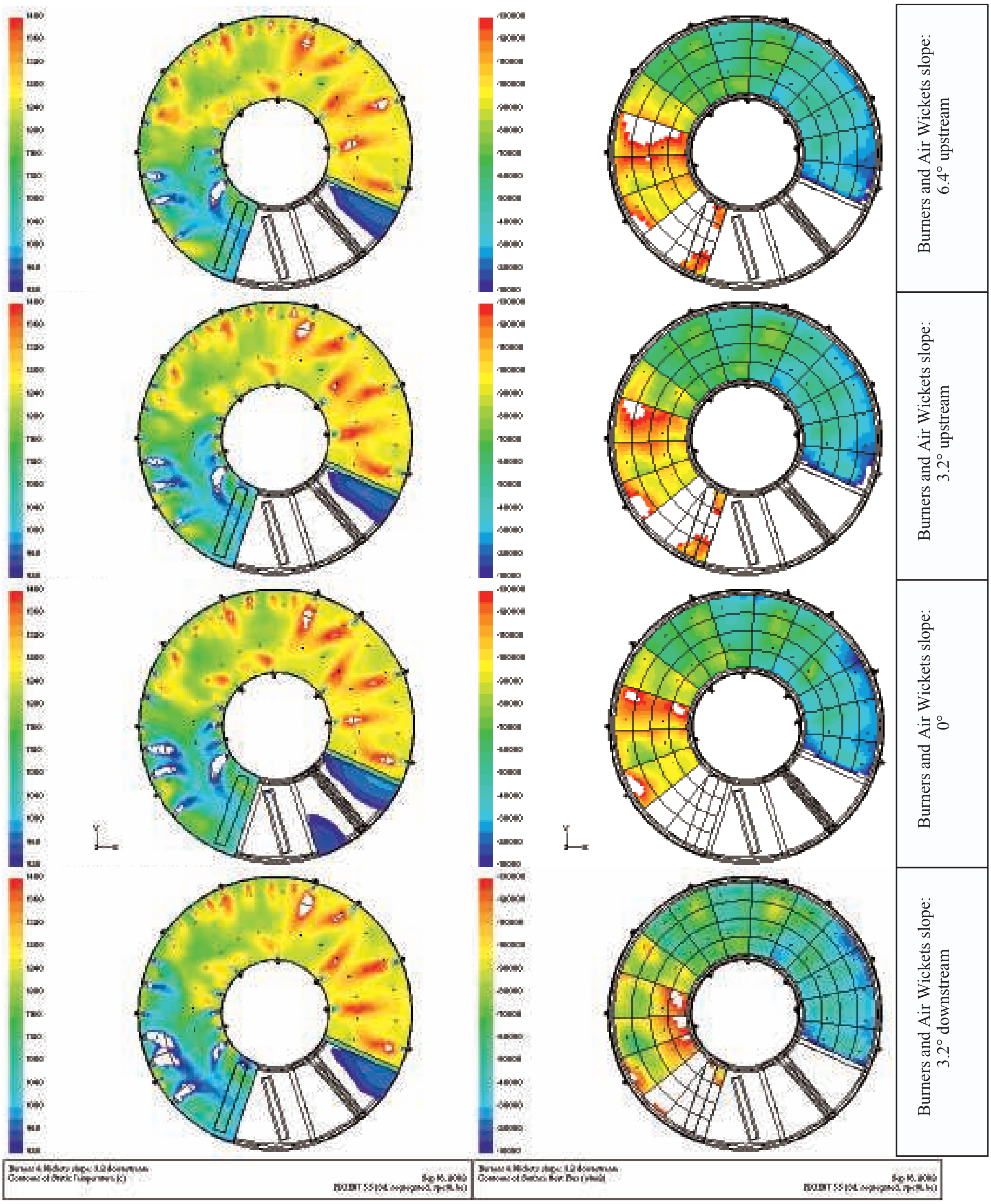


Figure 40. Burners and air wickets slope

2.6.2 CFD analysis of RHF discharging screw

A CFD study has been developed to verify the design of the DRI discharging screw. This report summarises the results of this optimisation study.

The thermal-fluid-dynamic analysis of the discharging screw has been carried out using the “FLUENT” software.

In particular, the CFD study aimed at determining the following design features:

- Pressure drop between water inlet and water outlet in reference operating conditions (full capacity operating conditions)
- Heat carried out by water, calculated in different thermal conditions of the discharge zone
- Maximum temperature of screw walls, calculated in different thermal conditions of the discharge zone

The CFD model considers the following boundary conditions:

- Hearth temperature in discharge zone
- Wall temperature in the discharge zone
- Water inlet flowrate and temperature

The model has been developed under two main conservative hypotheses:

- Stationary conditions at full capacity (which is the most critical operating condition)
- To simplify the geometry of the model, the screw blades are represented on straight lines (in this way the total surface of the blades is considered exposed to the heat radiation of the furnace).

The figures in the following pages show the following information:

- Screw geometry and grid details (Figure 41)
- Water streamlines and pressure drop details (Figure 42)
- Heat exchanged with the screw (Figure 43)
- Influence of different thermal condition in the discharging zone on heat transferred to the screw (Figure 44) and on maximum temperatures of the blades (Figure 45).

The results of the model confirm that the indirect cooling circuit of the discharging screw has been properly designed, in terms of water flowrate, water temperature and connections with the water inlet / outlet of the screw. The pressure drop and the blades temperatures are, in fact, acceptable, considering the heat flux of the discharging zone of the furnace and the geometry design of the screw.

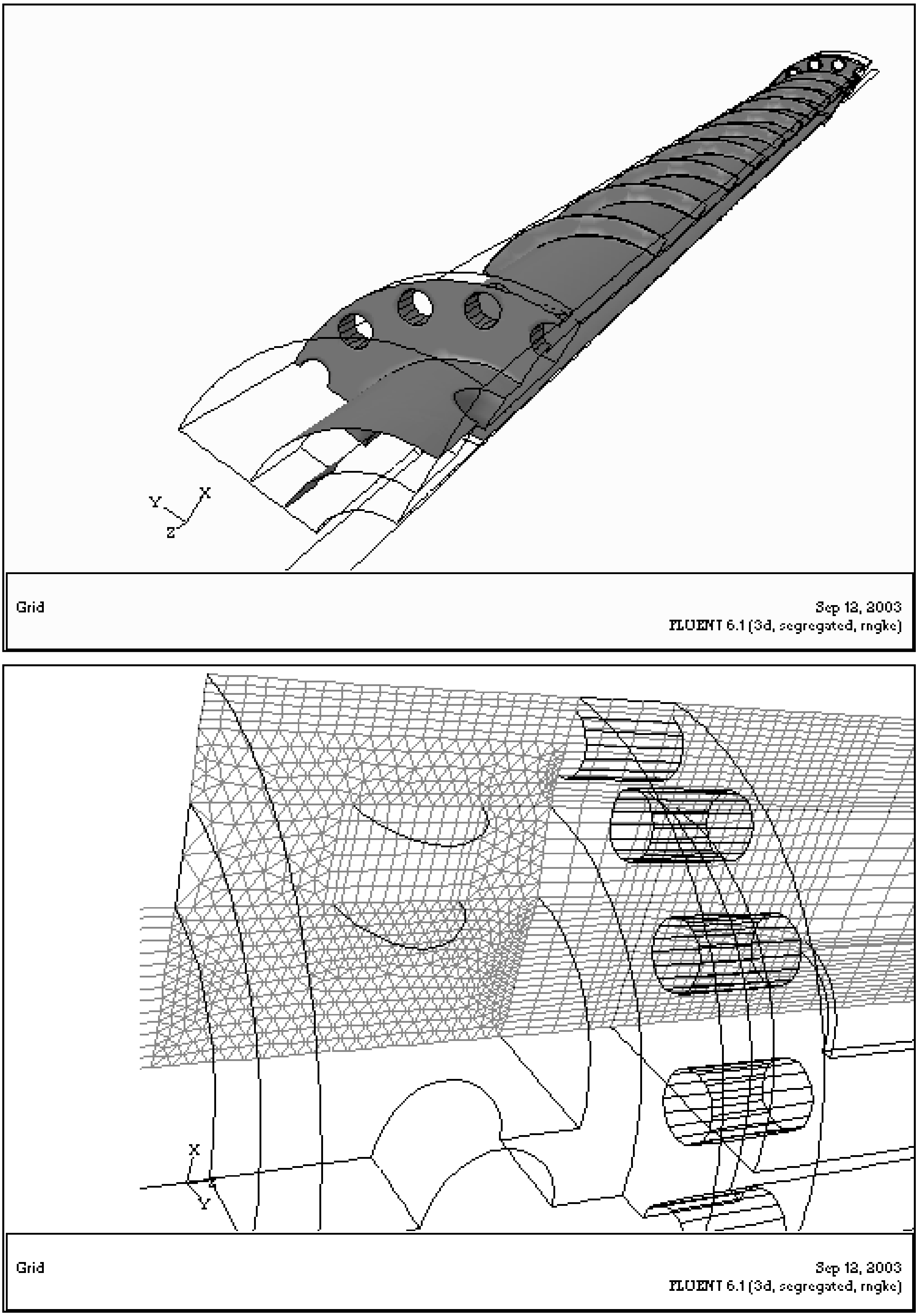


Figure 41. Screw geometry and grid details

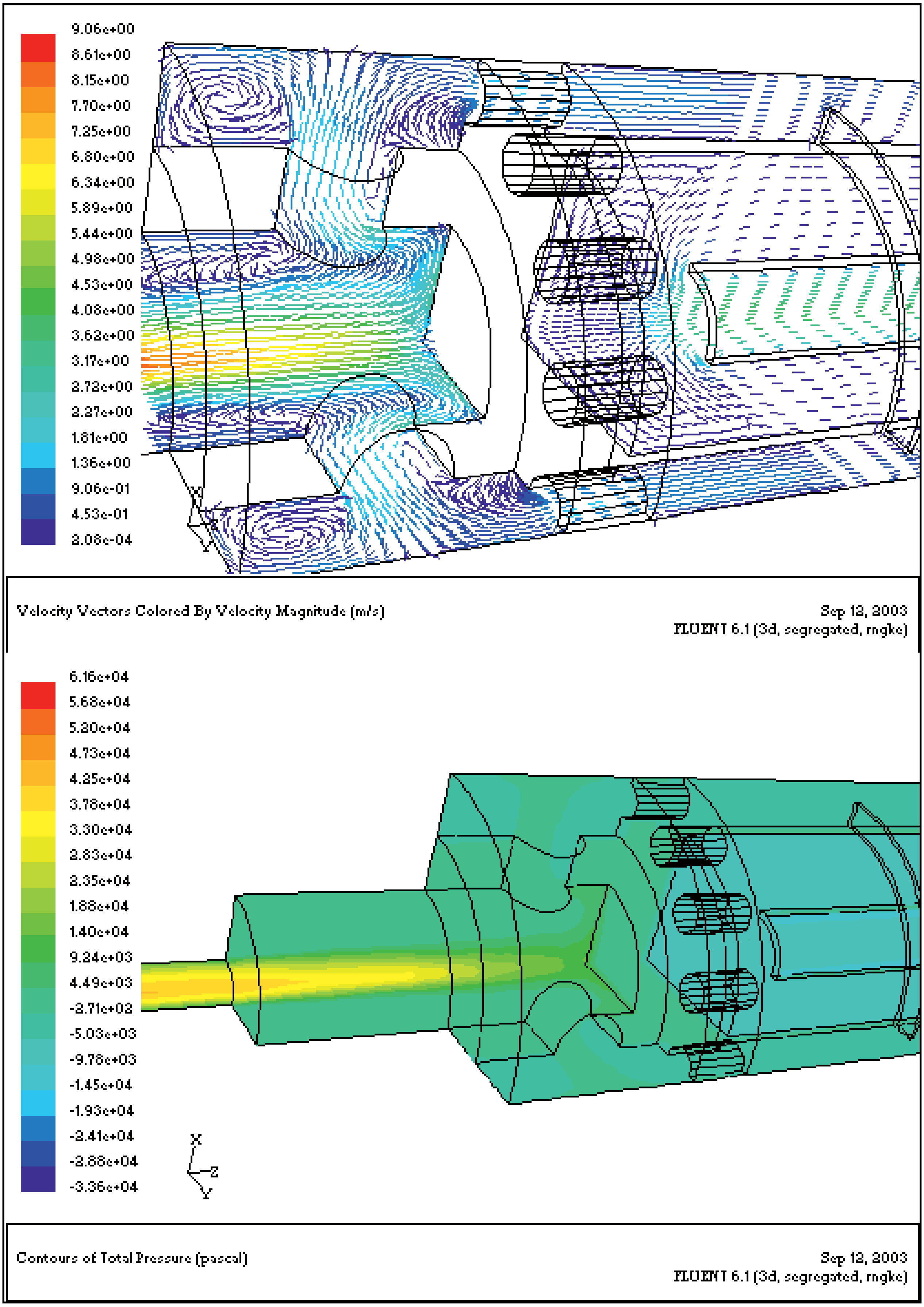


Figure 42. Water streamlined and pressure drop details

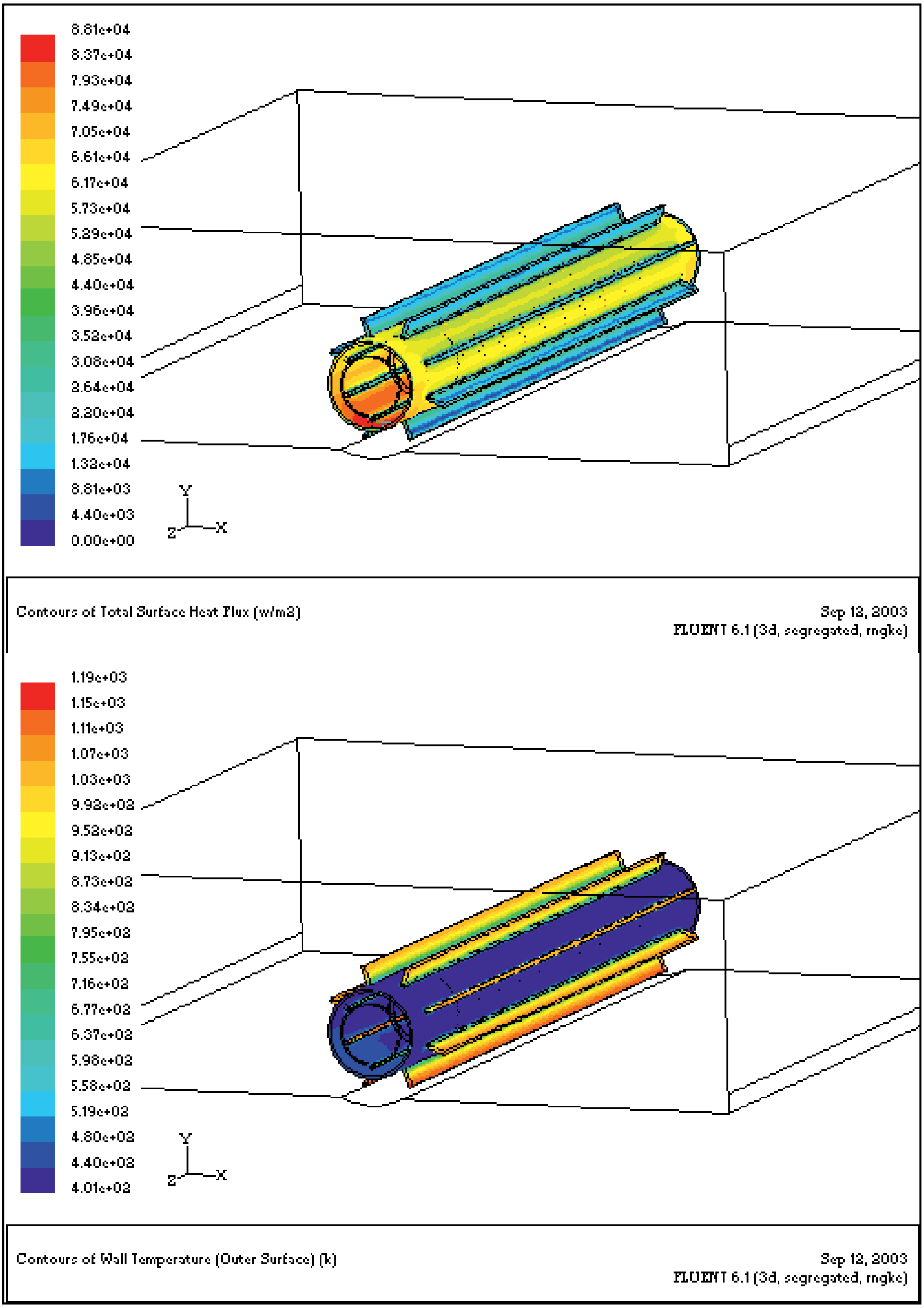


Figure 43. Analysis of the radiating heat exchanged with the screw

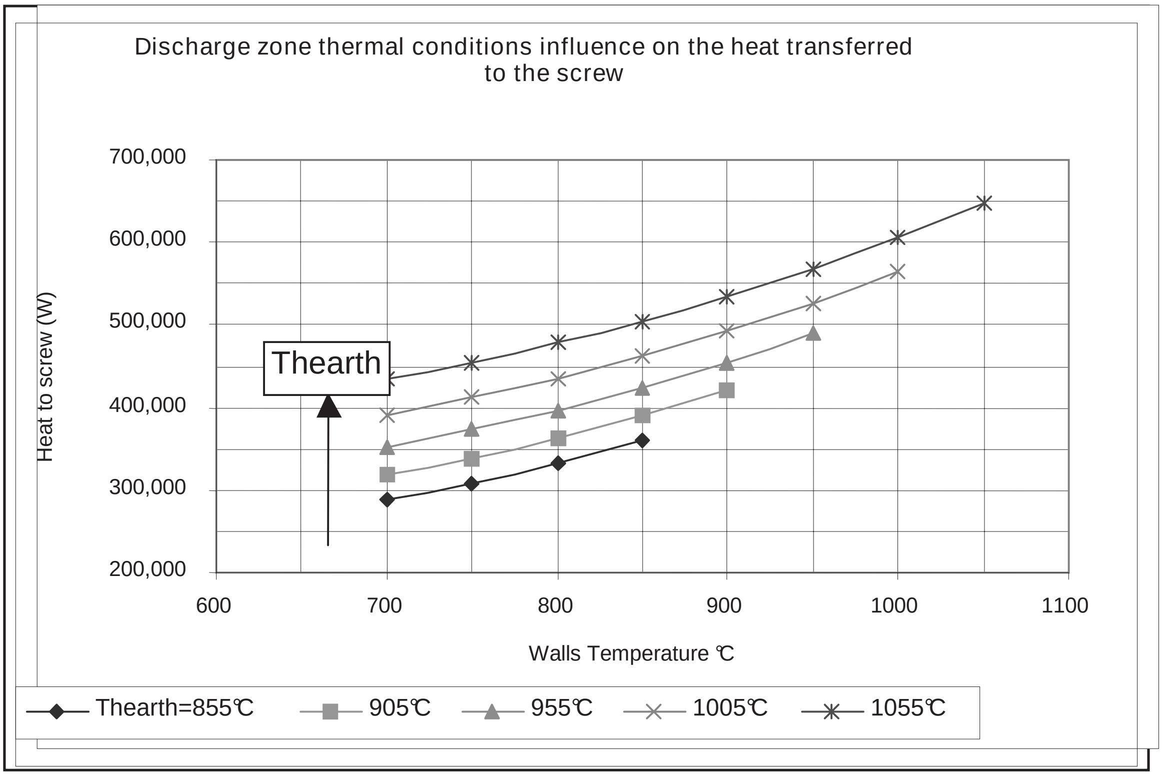


Figure 44. Heat transfer to the screw

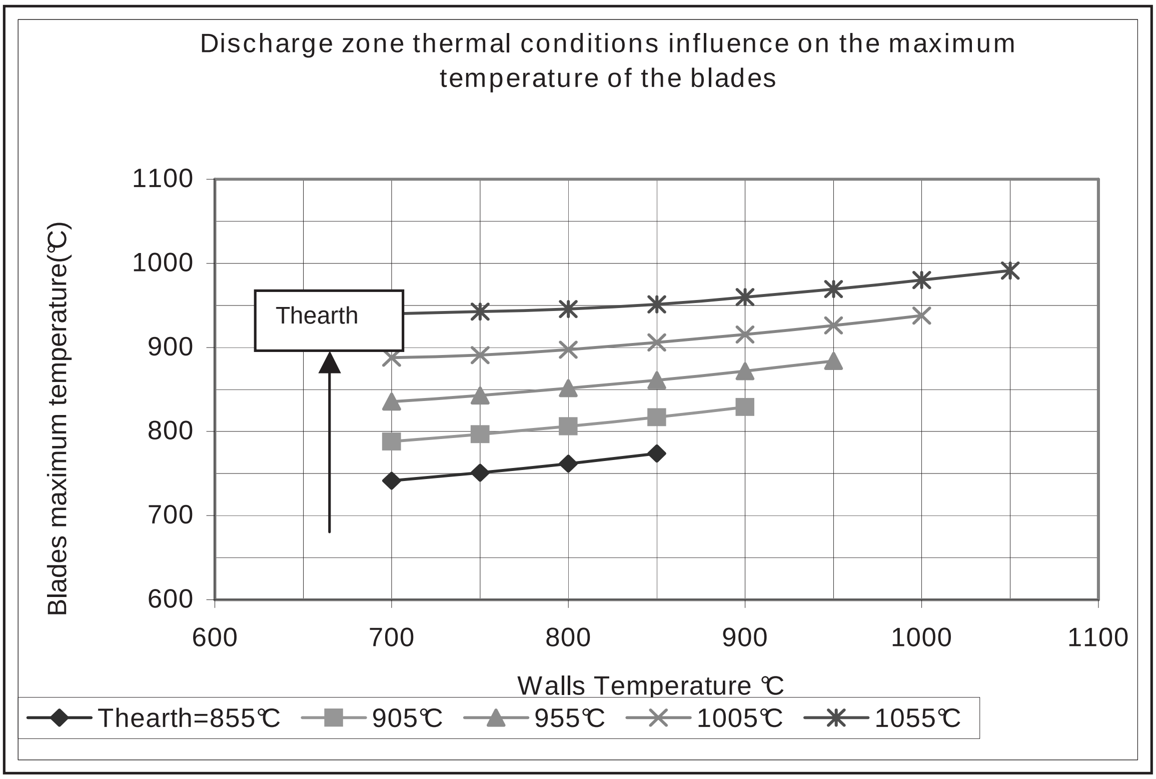


Figure 45. Screw: blades temperature

2.6.3 Stress thermal analysis of smelter refractory bricks

The study has been performed by the following steps:

- Study of the existing refractory brick, damaged during the first heating
  This step has given two fundamental results:
  - The design of the brick is not adequate to the heavy conditions to which it is exposed during the operation (i.e. very high temperatures on the hot face of the brick and very high temperature gradient between the hot side and the inner surface in contact with the cooled copper stripe). Due to its geometry and size, the brick is in fact subject to stresses that are not compatible with the mechanical characteristics of the refractory material.
  - The very low thickness of the expansion joints left between the bricks is not sufficient and has strongly contributed to increase the stresses on the bricks.

  To solve the problem of the damaged refractory, it is therefore necessary to design a new brick and to define a different erection procedure (a higher thickness for the expansion joints).

- Study of the new concept for the refractory brick
  This step has taken to the design of a new brick with characteristics that are adequate to the actual operating conditions.
  The new refractory bricks were installed during the stoppage foreseen for the erection of the green pellets system.

Fr both studies (*existing* and *new concept* brick) the model consists of a refractory brick equipped with a central slot (used to install the cooling copper stripe from the external part of the smelter).
A refractory castable (32 mm width) is installed between the external steel plate (15 mm width) and the refractory bricks.

Considering the brick geometry, symmetric on both sides, the analysis has been carried out on ¼ of the brick. The following factors / steps have been considered / carried out:

- Characteristics of the materials involved in the system under analysis (refractory, castable, steel)
- Definition of the geometrical model and of the appropriate geometry constraints
- Thermal analysis, which is performed using the temperatures measured by the thermocouples during plant operation.
  In particular the following temperatures have been considered to simulate the conditions occurred during the first heating: 1150 °C on the hot side of the brick, 172 °C on the inner side that is in contact with the copper stripe (this value is deriving from a study performed with FLUENT, on the basis of data collected during plant operation). A temperature gradient has also been considered for copper stripes, between 95 °C on the hot side and 80°C on the external side of the stripe.
- Definition of the structural model, using the thermal gradient resulting from the thermal analysis.
  For the outer castable and for the castable between the bricks, to better simulate the actual behaviour of contact and friction, not-linear elements have been used (elements not resisting to traction).
  For the *new concept* model, considering the effective distribution of expansion joints, it was sufficient to insert only one surface made of not-linear contact elements.
- Structural analysis, with the calculation of circumferential and Von Mises stress

In the following some detailed information relevant to the study is given:

- Materials specification (*existing* brick)
- Materials specification (*new concept* brick)
- Thermal analysis results (*existing* and *new concept* brick)
- Definition of the structural models (*existing* and *new concept* brick)
- Distribution of temperatures in the structural models (*existing* and *new concept* brick)
- Circumferential and Von Mises stress distribution (*existing* and *new concept* brick)

Measurement units

If not otherwise specified, the International System measurement units have been used.
In the graphs showing the results of the structure analysis [N, mm] is used, while for the thermal analysis [W, mm] is used.

MATERIALS SPECIFICATION (EXISTING BRICK)

Mechanical characteristics of the refractory brick

$E=$ 30.000 N/mm^2 (Elasticity module)
$\nu=$ 0.3 (Poisson coefficient)
$\alpha=$ 0.86 E-5 ° C^{-1} (Thermal expansion coefficient)
$k=$ 0.004 [W/mm°C] (Conductivity)

Mechanical characteristics of the castable between brick and steel

$E=$ 30.000 N/mm^2 (Elasticity module)
$\nu=$ 0.3 (Poisson coefficient)
$\alpha=$ 0.86 E-5 ° C^{-1} (Thermal expansion coefficient)
$k=$ 0.0015 [W/mm°C] (Conductivity)

Mechanical characteristics of the steel used for the external part of the vessel

$E=$ 200.000 N/mm^2 (Elasticity module)
$\nu=$ 0.3 (Poisson coefficient)
$\alpha=$ 1.2 E-5 ° C^{-1} (Thermal expansion coefficient)
$k=$ 0.03 [W/mm°C] (Conductivity)

MATERIALS SPECIFICATION (NEW CONCEPT BRICK)

Mechanical characteristics of the refractory brick

$E=$ 1550 [N/mm^2] (0°C)
2100 [N/mm^2] (1500°C) (Elasticity module)
$\nu=$ 0.3 (Poisson coefficient)
$\alpha=$ 0.4 E-5 [° C^{-1}] (1000°C) (Thermal expansion coefficient)
0.375 E-5 [° C^{-1}] (1600 °C)
$k=$ 0.0032 [W/mm°C] (500°C) (Conductivity)
0.0030 [W/mm°C] (1000°C)

Mechanical characteristics of the castable between brick and steel

$E=$ 300 N/mm^2 (Elasticity module)
$\nu=$ 0.3 (Poisson coefficient)
$\alpha=$ 0.86 E-5 ° C^{-1} (Thermal expansion coefficient)
$k=$ 0.0015 [W/mm°C] (Conductivity)

Mechanical characteristics of the steel used for the external part of the vessel

$E=$ 200.000 N/mm^2 (Elasticity module)
$\nu=$ 0.3 (Poisson coefficient)
$\alpha=$ 1.2 E-5 ° C^{-1} (Thermal expansion coefficient)
$k=$ 0.030 [W/mm°C] (Conductivity)

THERMAL ANALYSIS

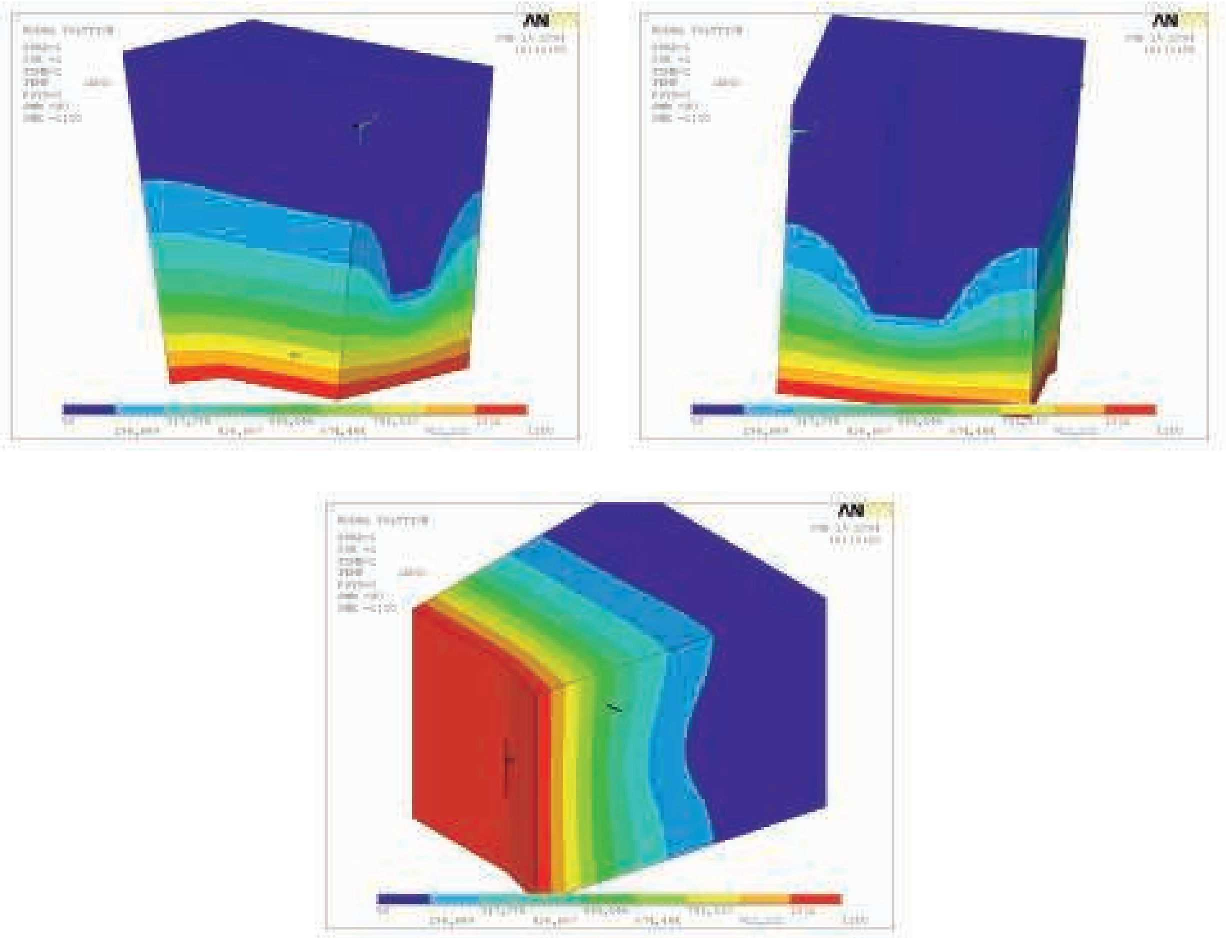


Figure 46. Existing brick - Thermal analysis

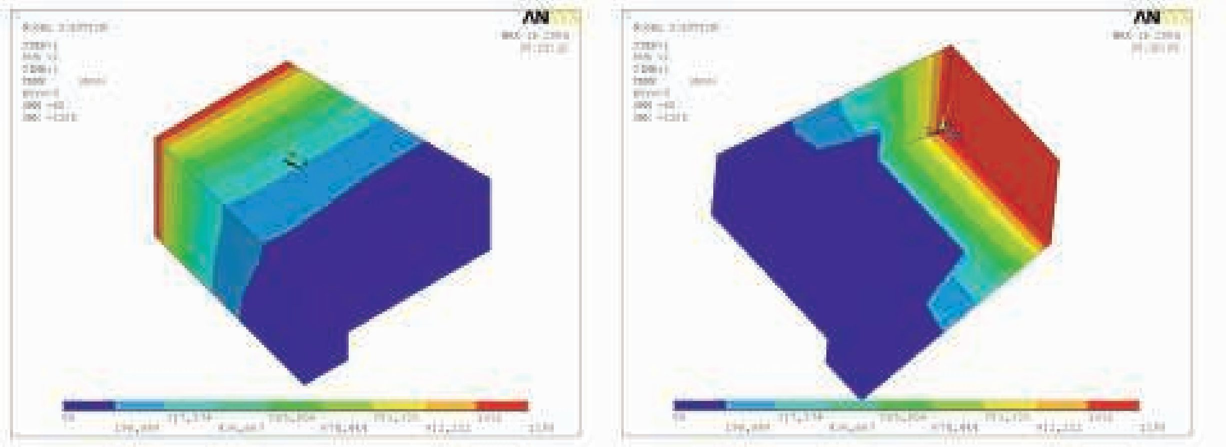


Figure 47. New concept brick - Thermal analysis

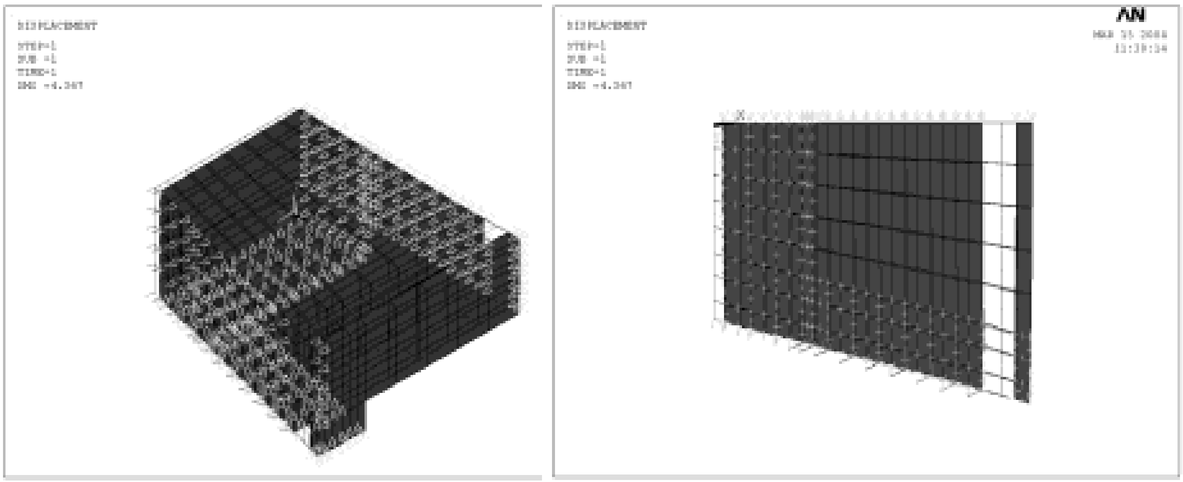


Figure 48. Existing brick - ANSYS model with constraints + relevant top view

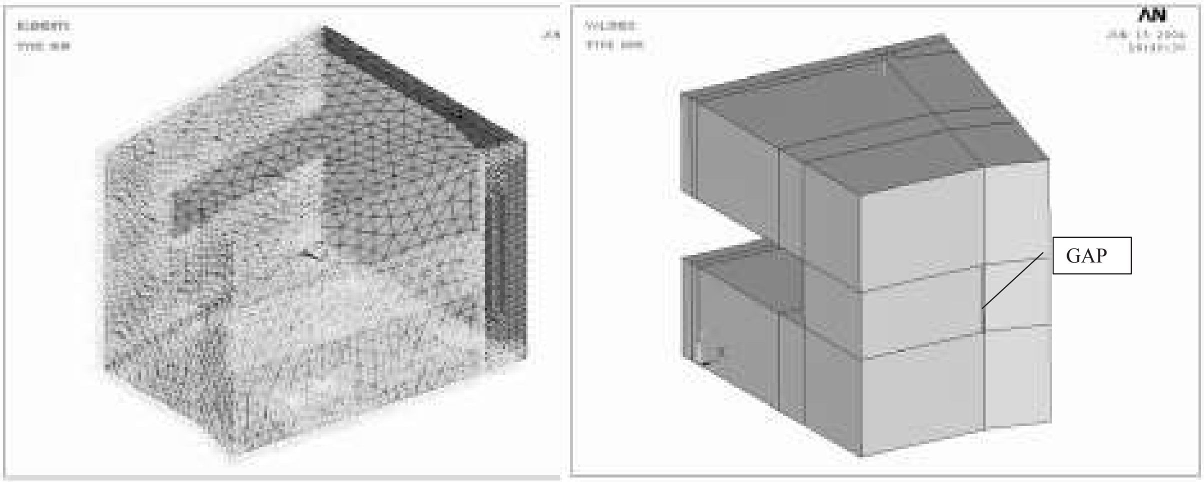


Figure 49. New concept brick - ANSYS model with constraints and model with gap

DISTRIBUTION OF TEMPERATURES IN THE STRUCTURAL MODEL

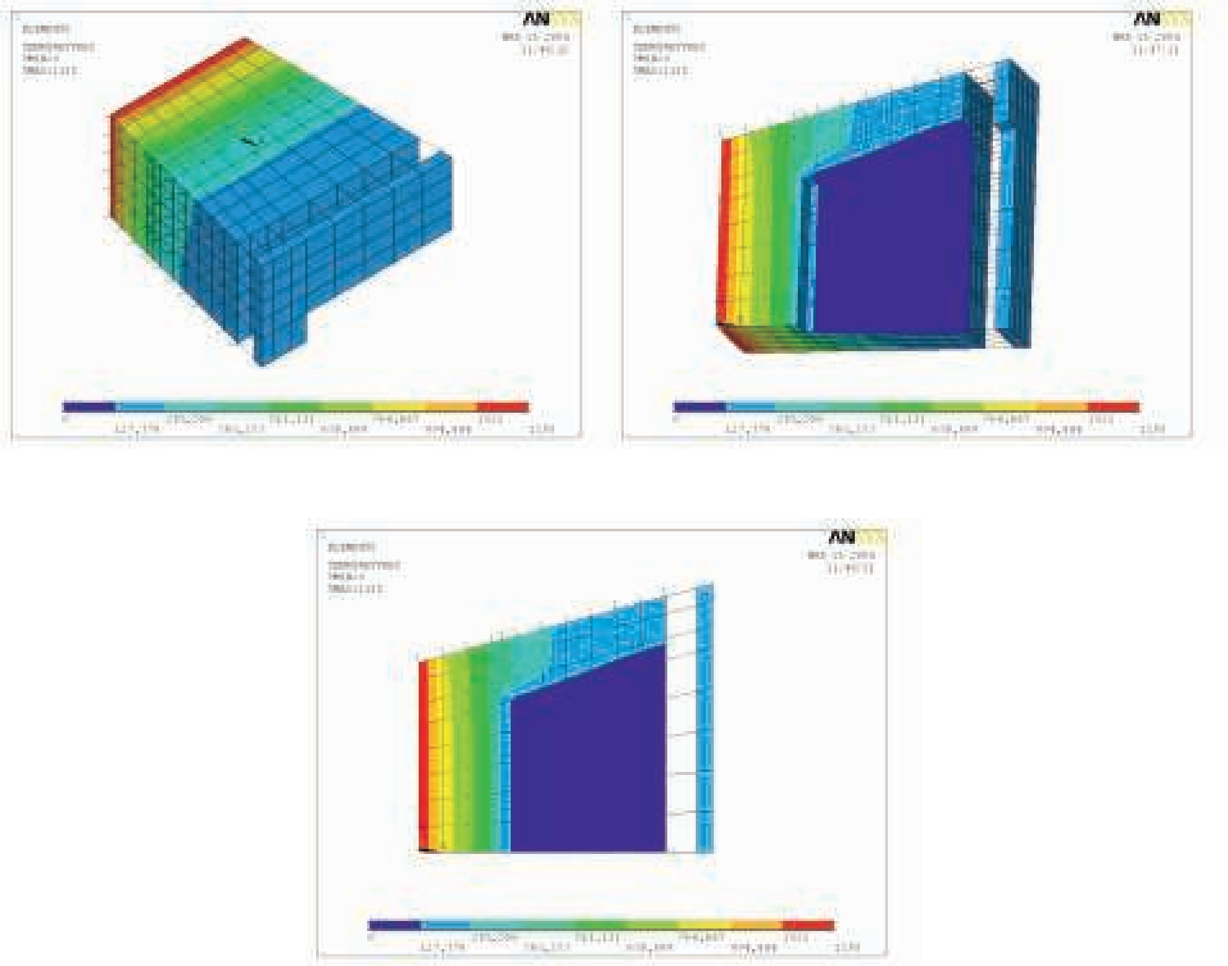


Figure 50. Existing brick - Distribution of temperatures in the structural model

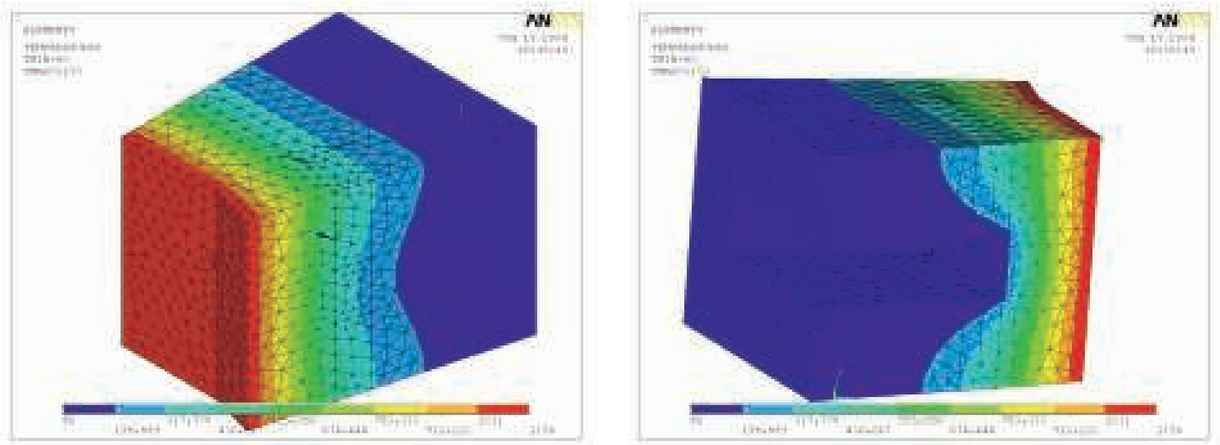


Figure 51. New concept brick - Distribution of temperatures in the structural model

STRESSES

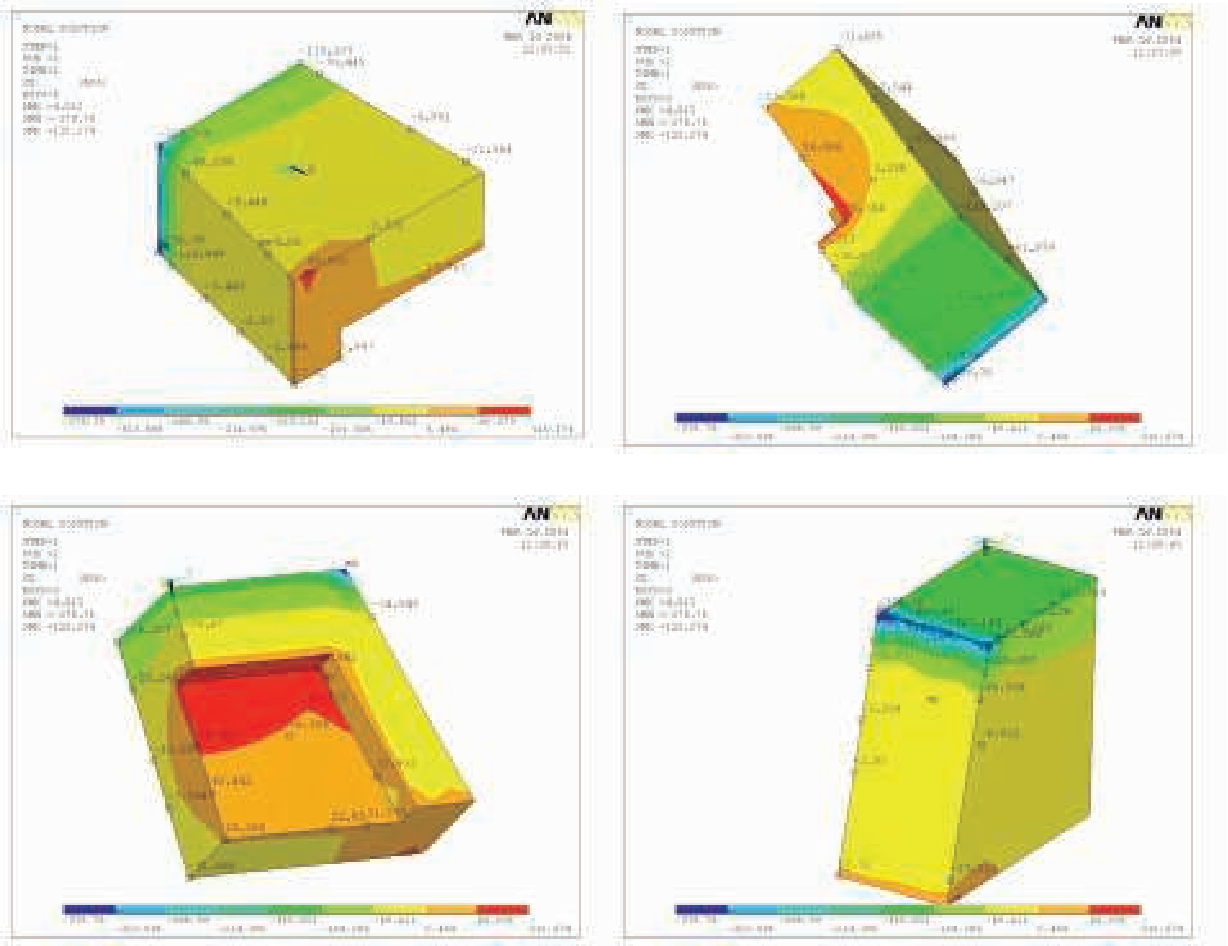


Figure 52. Existing brick - Circumferential stress in the brick

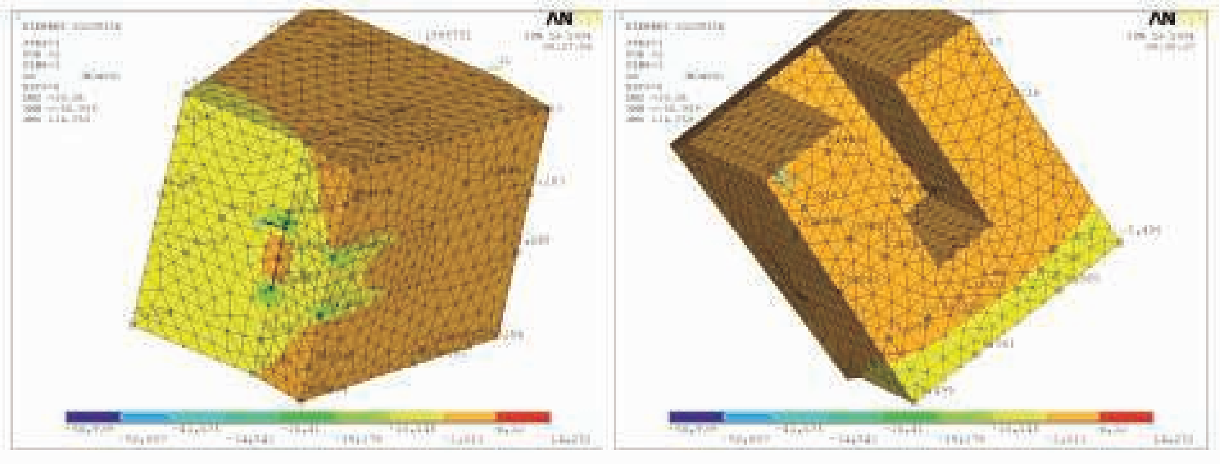


Figure 53. New concept brick - Circumferential stress in the brick

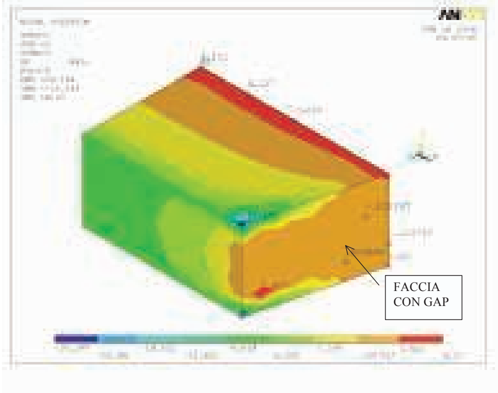


Figure 54. New concept brick - Circumferential stress in expansion joint area

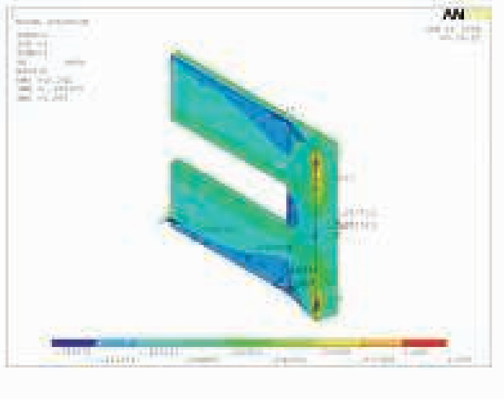


Figure 55. New concept brick - Circumferential stress in the layer of insulating castable

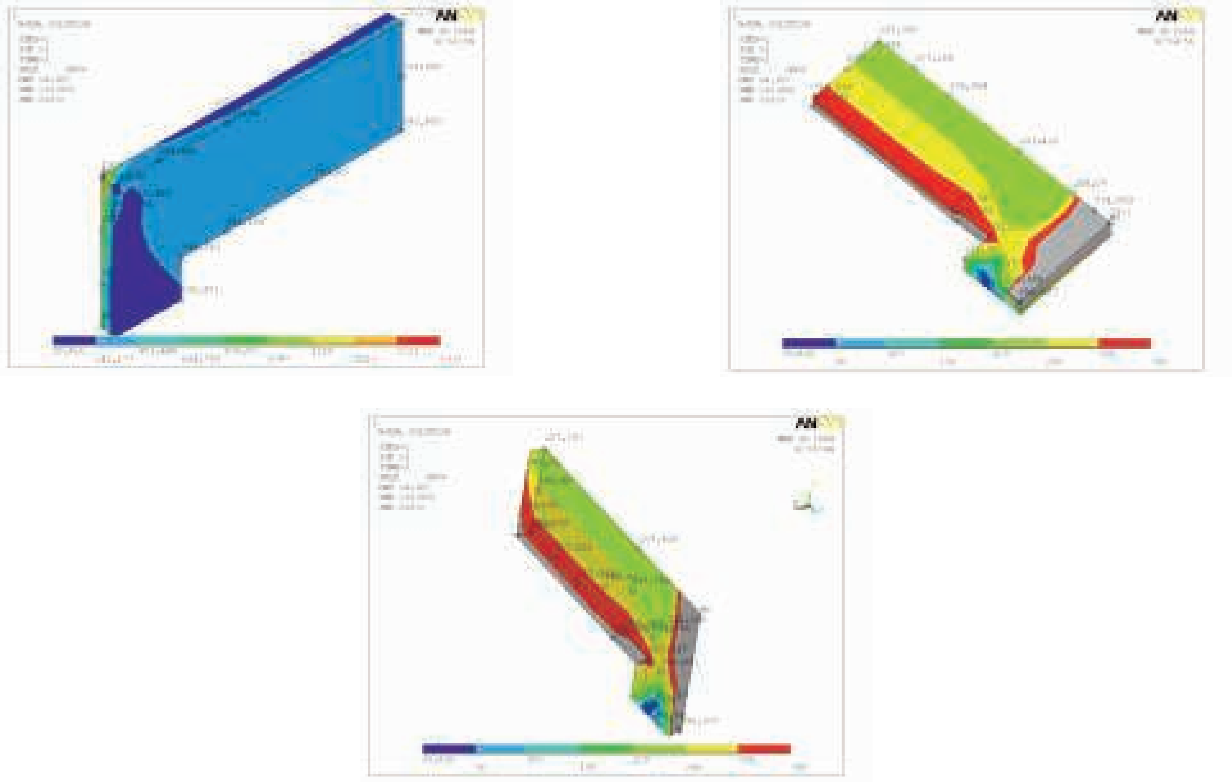
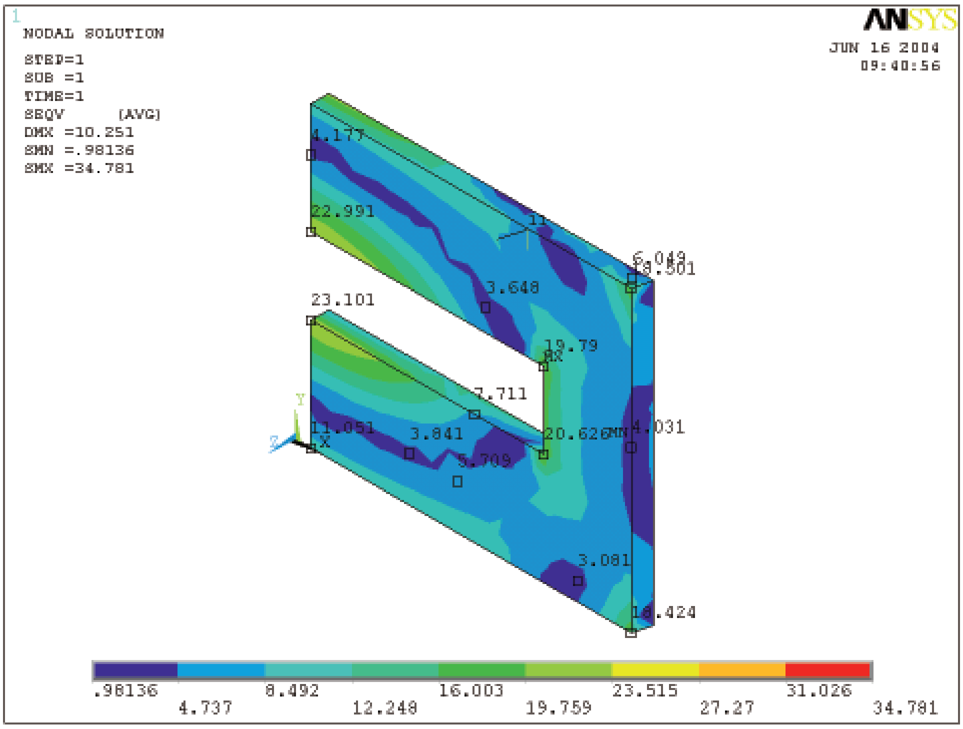


Figure 56. Existing brick - Von Mises stress in the steel plate



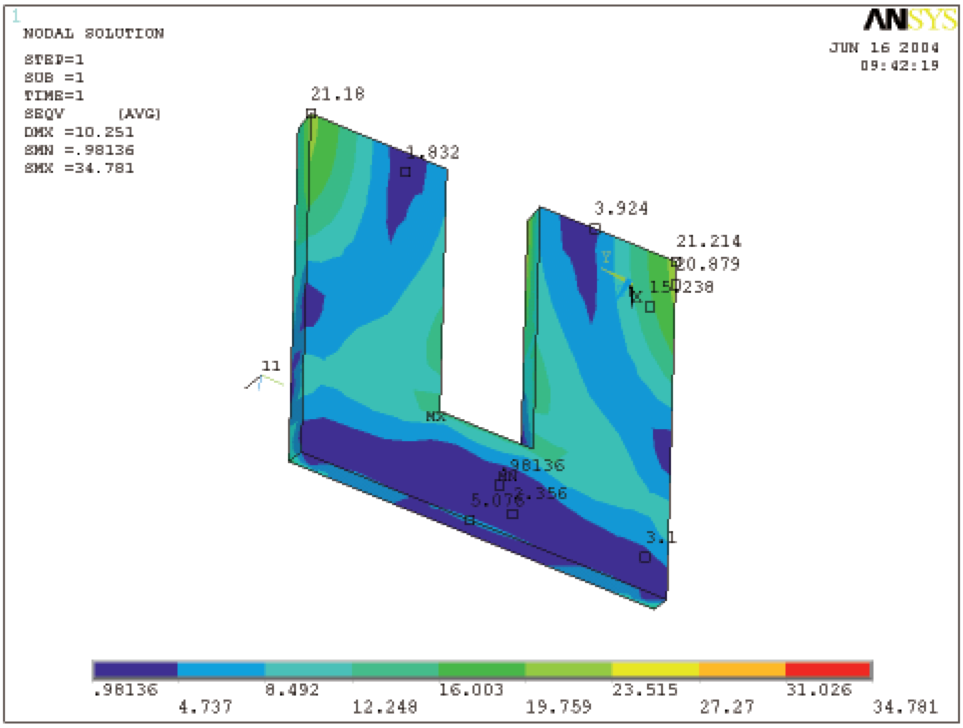


Figure 57. New concept brick - Von Mises stress in the steel plate

2.6.4 1-dimensional model material and thermal balance

This model program splits the furnace in a number of slices along its circumference. For each slice a material and thermal balance is calculated, in order to predict the chemical composition and the temperature both of the pellets bed and of the counter-flowing gas. The material balance takes into account the following chemical reactions regarding the bed:

- Moisture evaporation
- Release of coal volatile matters
- Calcinations of Ca and Mg carbonates
- Iron oxide reduction
- Zinc and lead reduction and vaporisation
- Alkali's evaporation
- Carbon gasification (solution loss reaction)
- Carbon combustion

The kinetics coefficients for the above reaction rates have been determined by tests results realised at CSM Dalmine in their experimental batch furnace.

The kinetics of the chemical reaction taking place in the gas phase, which are mainly controlled by the fluid-dynamics of the gas mixing, have been tuned on the basis of the CFD simulation model results.
Furthermore, the heat exchange between gas and bed and refractory is calculated, taking also into account the heat loss through the hearth and through the walls. Of course, the heat balance of the hearth is done taking into account its movement and its thermal capacity.

Input Data:

- Furnace geometry
- Hearth rotation speed
- Green pellets mass flow rate, temperature and chemical composition
- Mass flow rate, temperature and chemical composition of fuel, combustion and wickets air, for each zone of the furnace
- Thermal properties of the pellets bed and of the hearth (specific heat, conductivity)
- Tuning factors for the calculation of the heat transfer between gas, walls and bed
- Tuning factors for the calculation of the thermal losses
- Tuning parameters (obtained from reduction tests and from data coming from other plants) for the kinetics of the different reactions
-

Output Data (obtained with subsequent iterations):

- Longitudinal profile of the degree of reduction reactions of ferrous and non-ferrous oxides
- Longitudinal profile of the degree of carbon burn-out
- Longitudinal profile of release of volatiles and of water evaporation
- Longitudinal profile of gas composition
- Longitudinal profile of bed temperature at various levels and profile heat flux
- Profile of all the different heat losses (walls, hearth, water cooling, etc)

In the following figures an example of longitudinal profiles of the mentioned variables is presented. As shown it can be noticed the good agreement that has been found between CFD simulations and test data, regarding the gas-solid heat fluxes distribution.

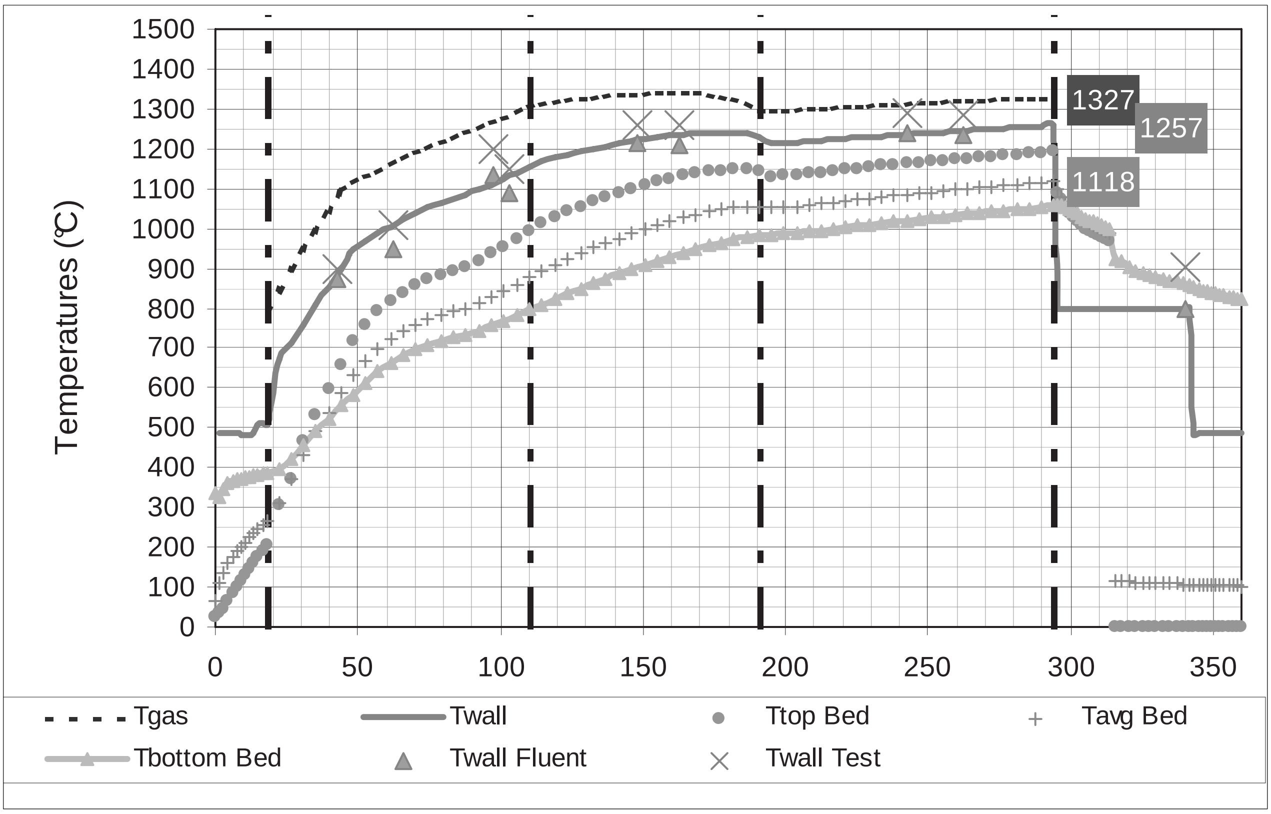


Figure 58. Longitudinal profile of temperatures inside the RHF

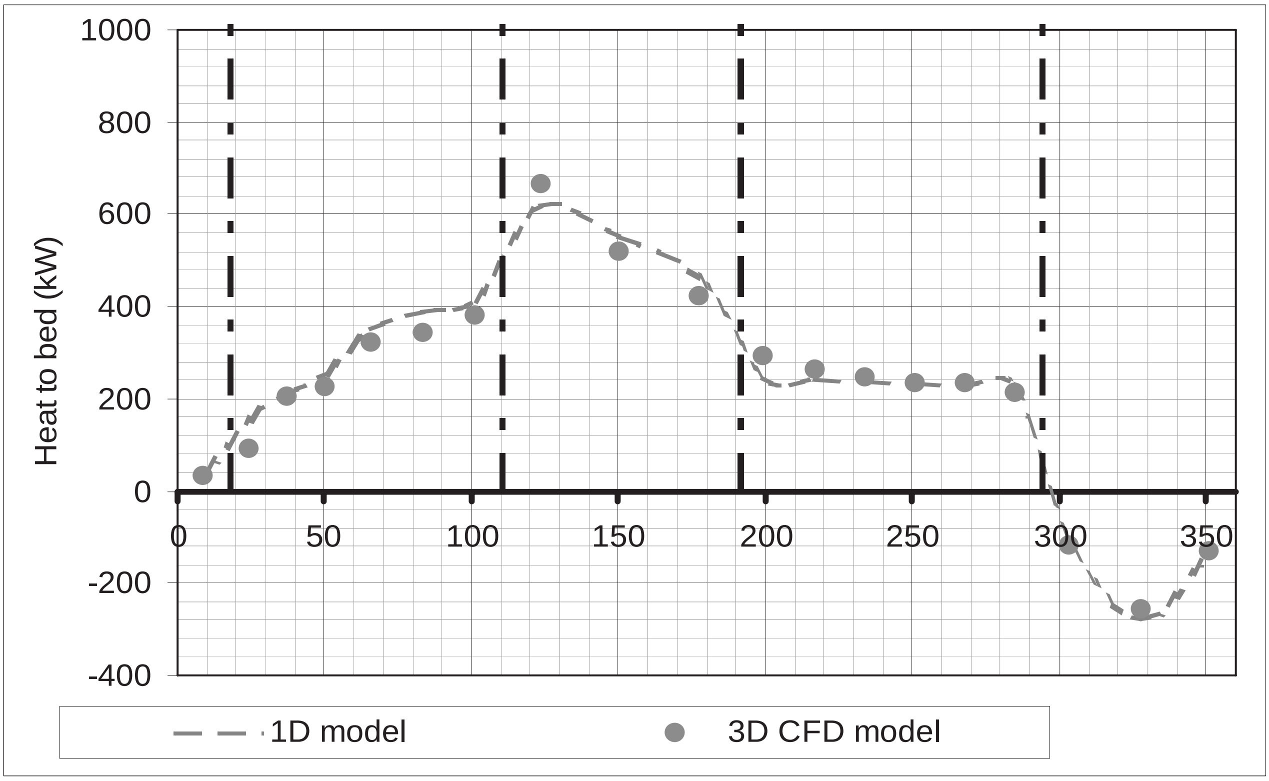


Figure 59. Longitudinal profile of heat transferred to bed

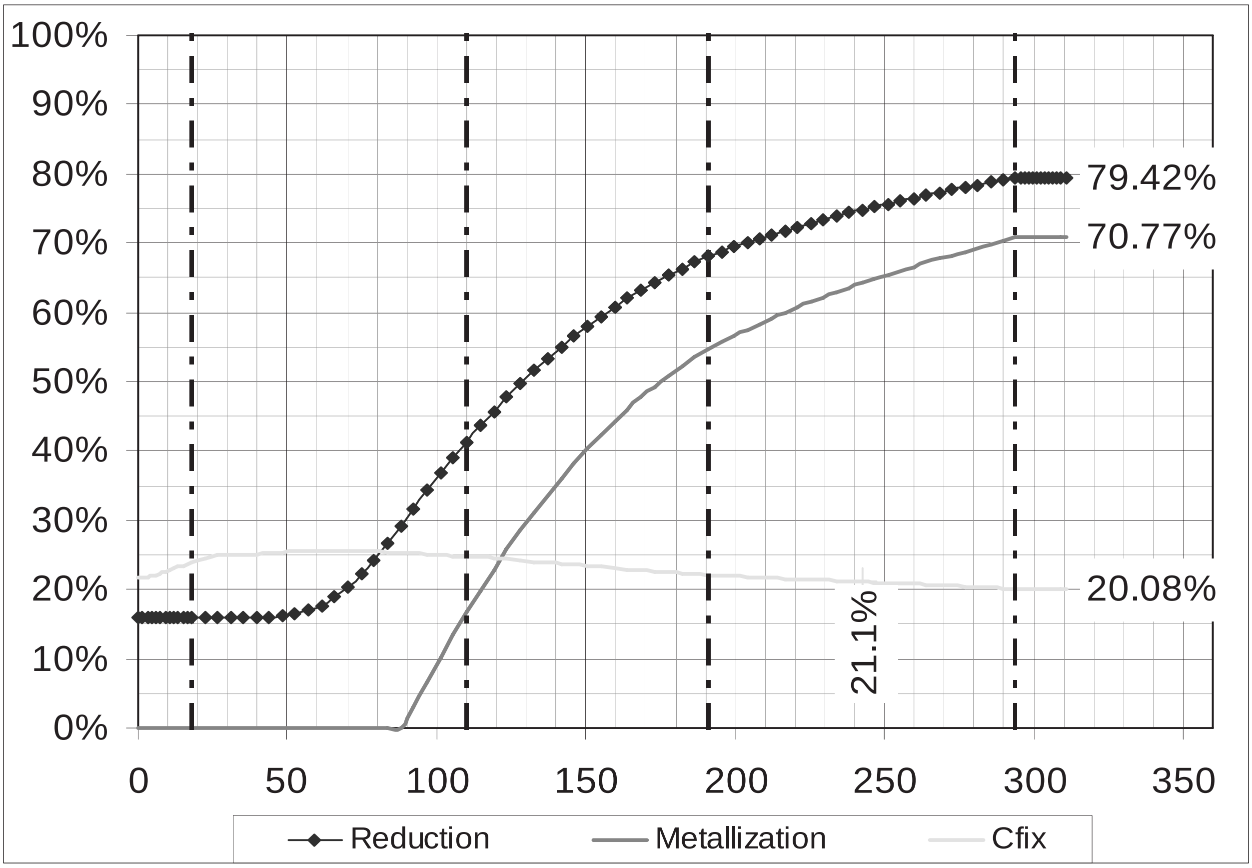


Figure 60. Longitudinal profile of reduction, metallisation and carbon content

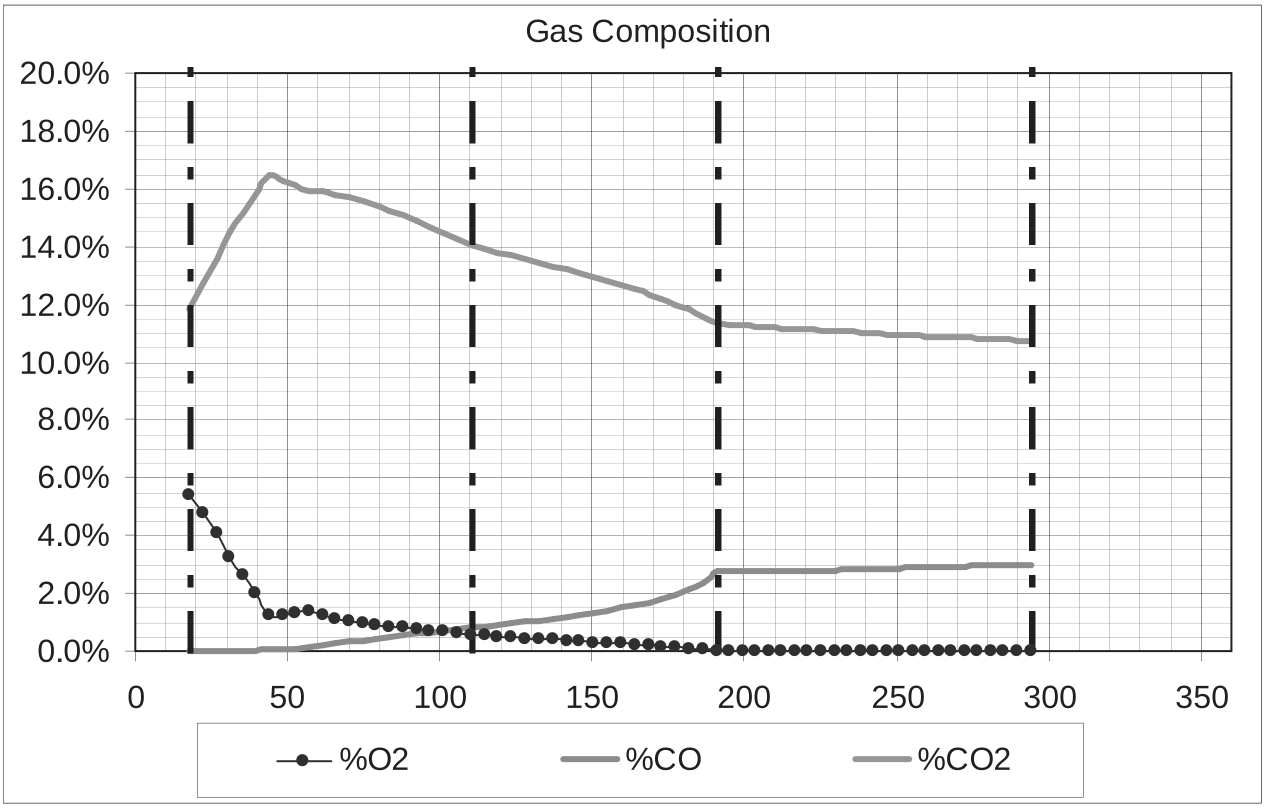


Figure 61. Longitudinal profile of gas composition

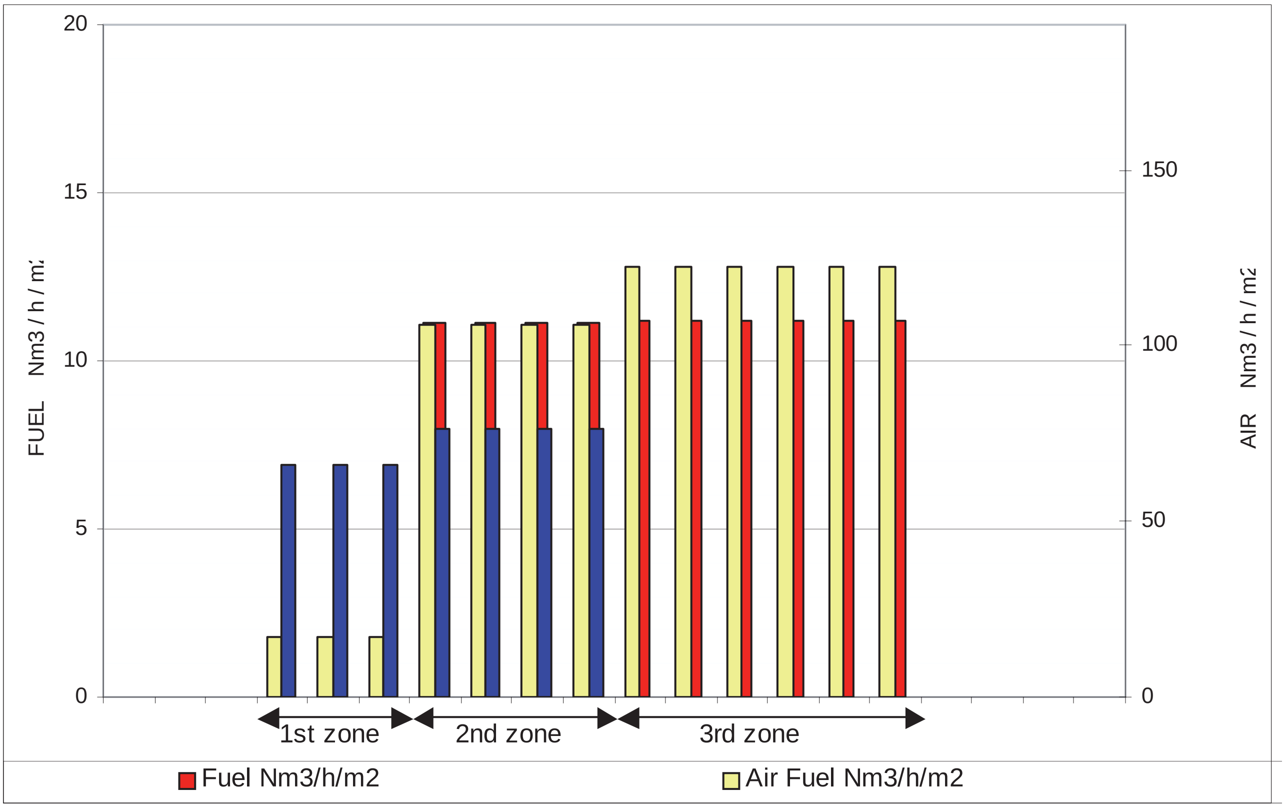


Figure 62. Longitudinal distribution of fuel and air inside the furnace

2.6.5 CFD simulation model

The CFD model utilises a 3-D mesh, through which thermal, chemical and fluid-dynamic analysis are carried out. Input data are temperatures, compositions and mass flow rates of inlet fluids, temperature and radiating properties of boundaries.

The furnace simulation has been carried out analysing the complete furnace geometry including the geometry of burners and wickets nozzles (paragraph 2.6.1), the discharge screw (simulated as a cylinder having a global thermal coefficient obtained by other suitable CFD simulations, paragraph 2.6.2), the pellet feeder, the off gas duct, the water seals.

The furnace geometry has been divided into 400,000 calculation cells.

The following models have been used to solve fluid-dynamic and kinetic equations:

▪ Turbulent Model:	K-Epsilon model
▪ Radiation Model:	DO model
▪ Chemical Model:	“Species Transport” as per FLUENT manual

The CFD furnace model calculates the chemical reactions and the fluid-dynamic patterns in the gaseous phase, taking into account the material and energy flows between the cells and the boundaries: the walls, the roof, the discharge screw, defined as boundaries, exchange energy with the furnace cells, according to the temperatures profiles of the furnace and of heat flows coefficients, calculated by thermal exchange model.

The bed is defined as a boundary and interacts with the furnace exchanging both energy and mass with it, calculating the kinetics of combustion in the gaseous phase of the CO/CO2 mixture exiting from the bed: the pellets bed has been modelled by dividing it into 19 angular zones, in which we can suppose to have the same chemical and thermal behaviour, and by simulating each one of these zones as "walls" having a given temperature (obtained by 1-D model balance) which are sources of gaseous emissions (temperature, composition and mass flow of these emissions have been obtained by 1-D model balance). The CFD results are used to change, if necessary, the tuning factors in the 1-D model, and to recalculate the bed temperature and reduction profiles of the bed, iterating the two models aiming to reach a convergence.

After the convergence of the 3D CFD and 1-D model simulation, the heat exchanged between the gas and the bed, the walls and gas temperature, the walls thermal losses and the off gas composition have the same values in both models.
Some examples of CFD model results, is presented below. In particular the following figures are reported:

- 3-D modellisation of the Rotary Hearth Furnace (Figure 63)
- Hearth thermal distribution (Figure 64)
- Heat transferred to the bed (Figure 65)
- Roof and side walls temperatures (Figure 66)
- Gas velocity over the bed (Figure 67)
- Burners and air wickets section – temperatures (Figure 68)
- CO fraction over the bed (Figure 69)
- O2 fraction over the bed (Figure 70)

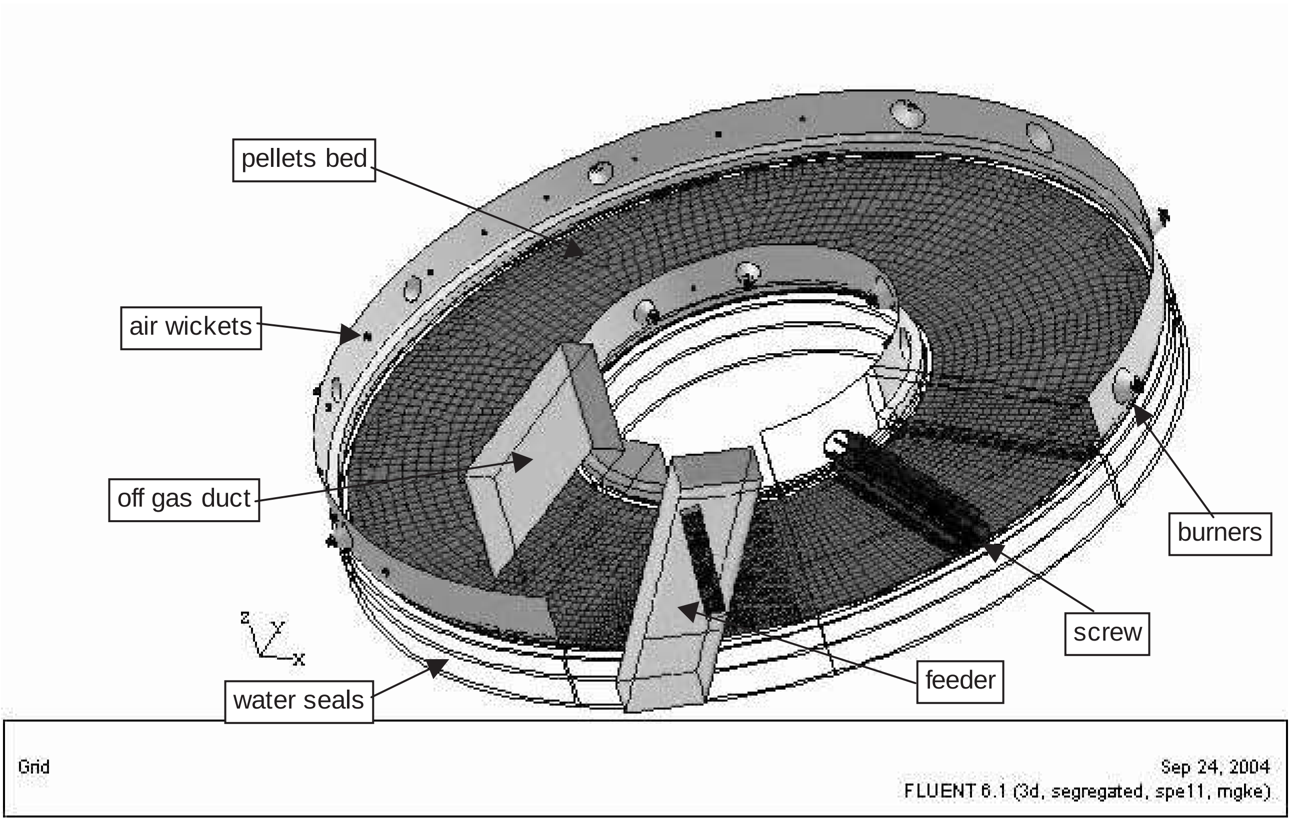
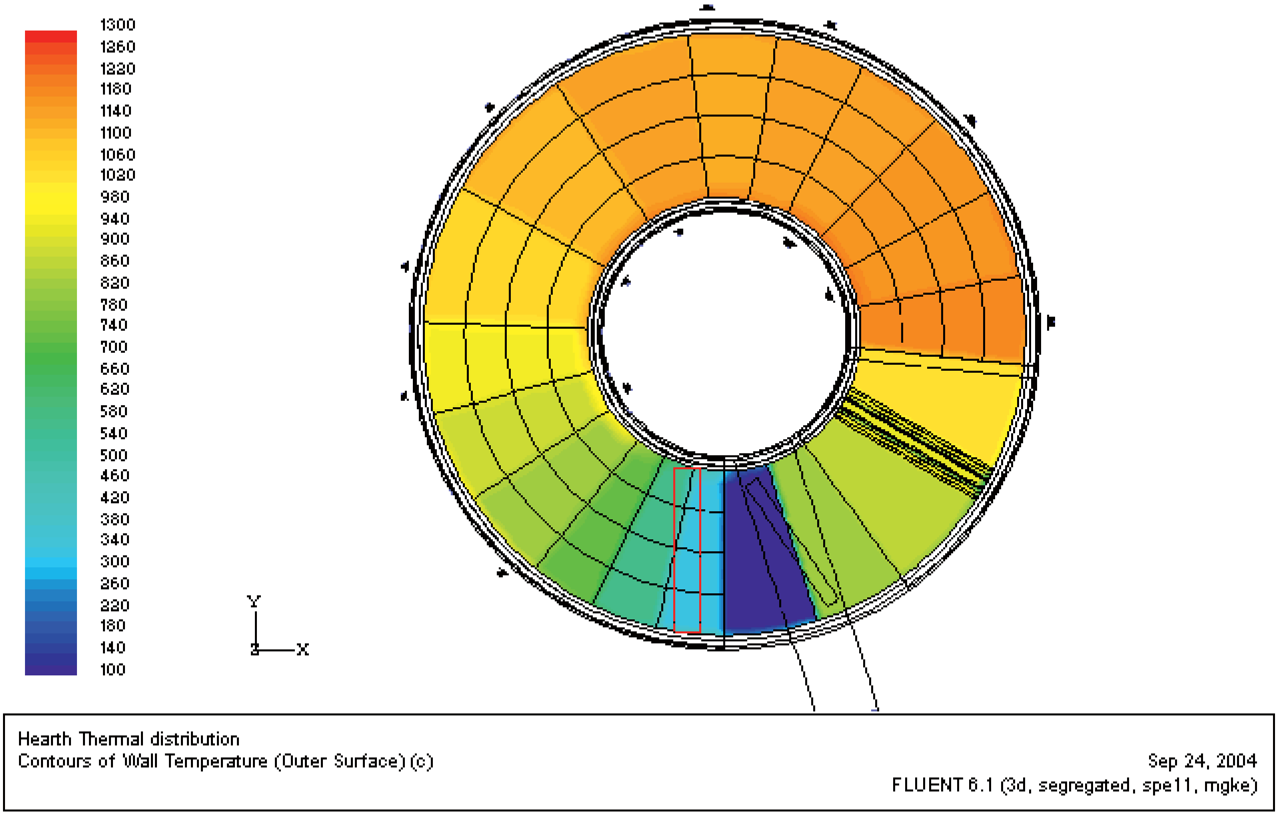


Figure 63. CFD 3-D model - Modellisation of the Rotary Hearth Furnace

Figure 64. CFD 3-D model - Hearth thermal distribution



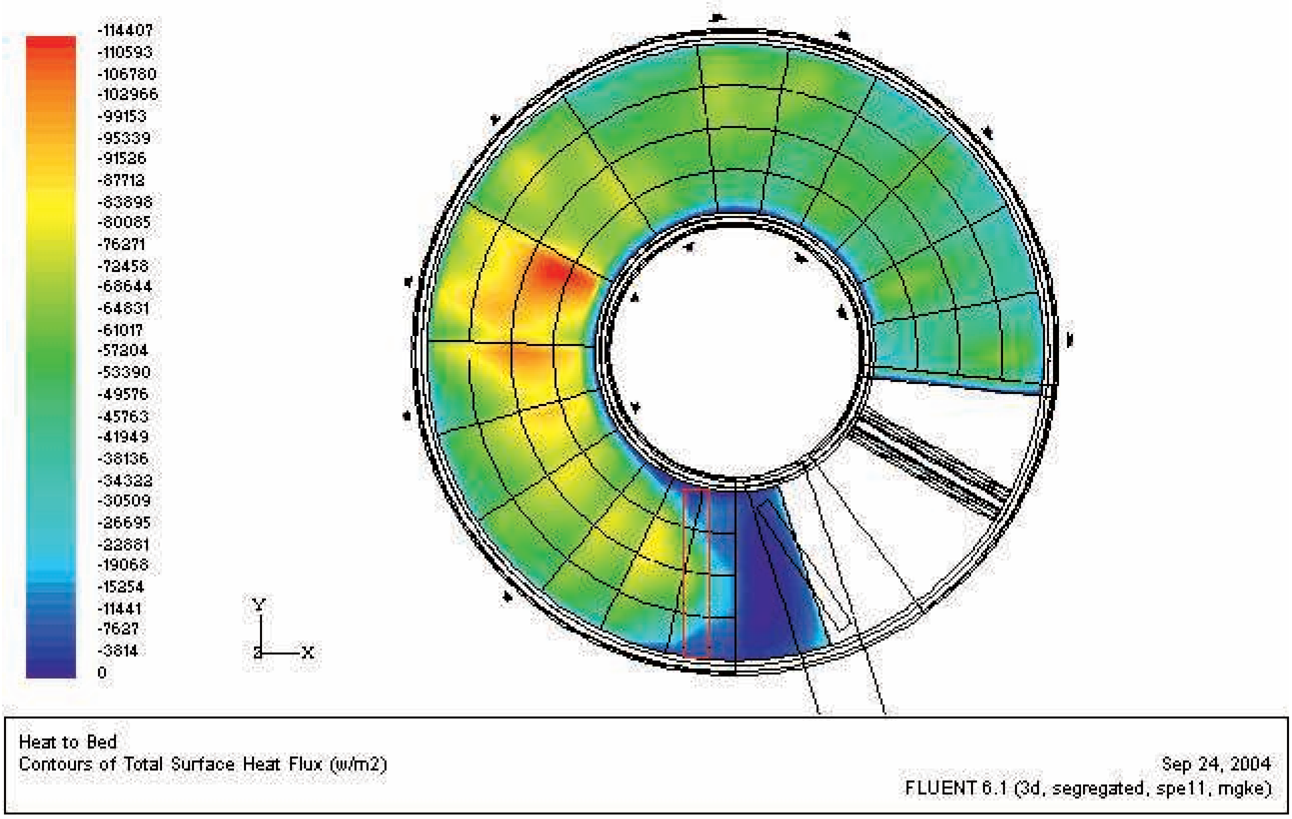


Figure 65. CFD 3-D model - Heat flux to the bed

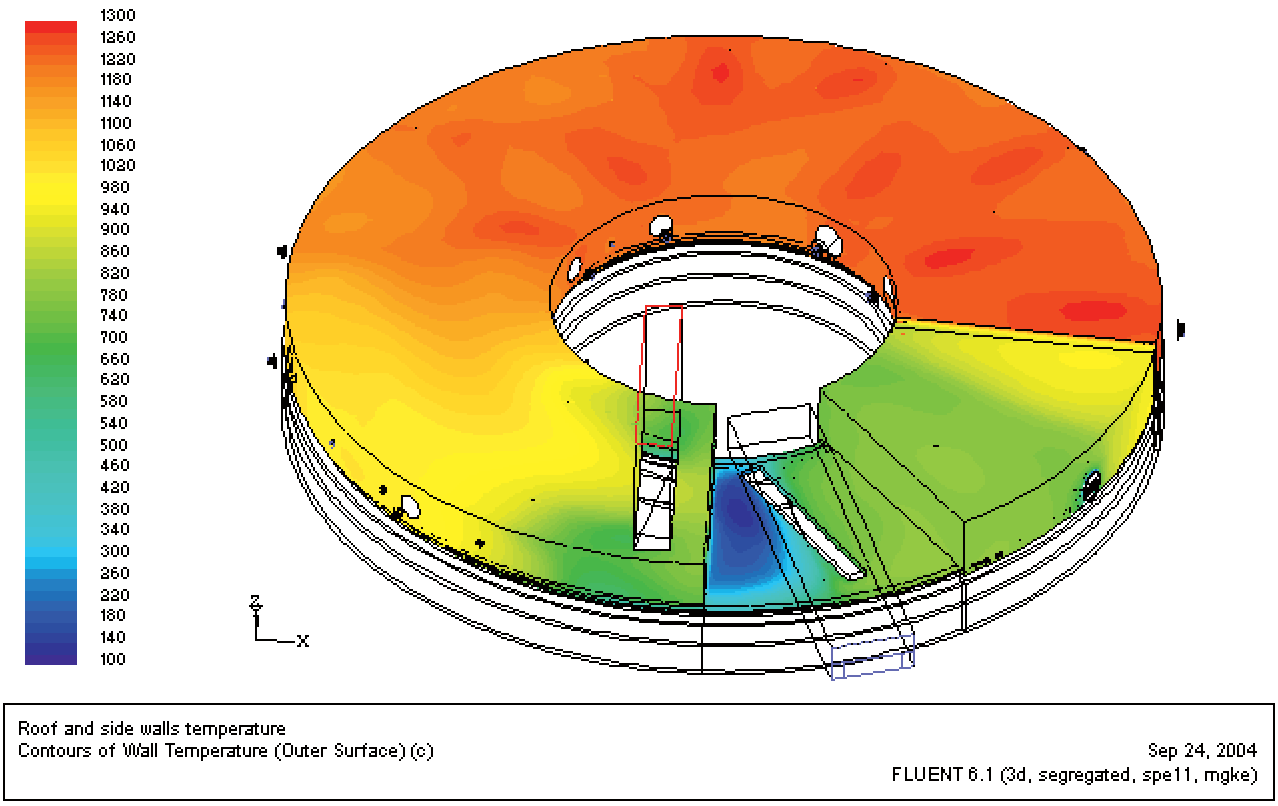


Figure 66. CFD 3-D model - Roof and side wall temperatures

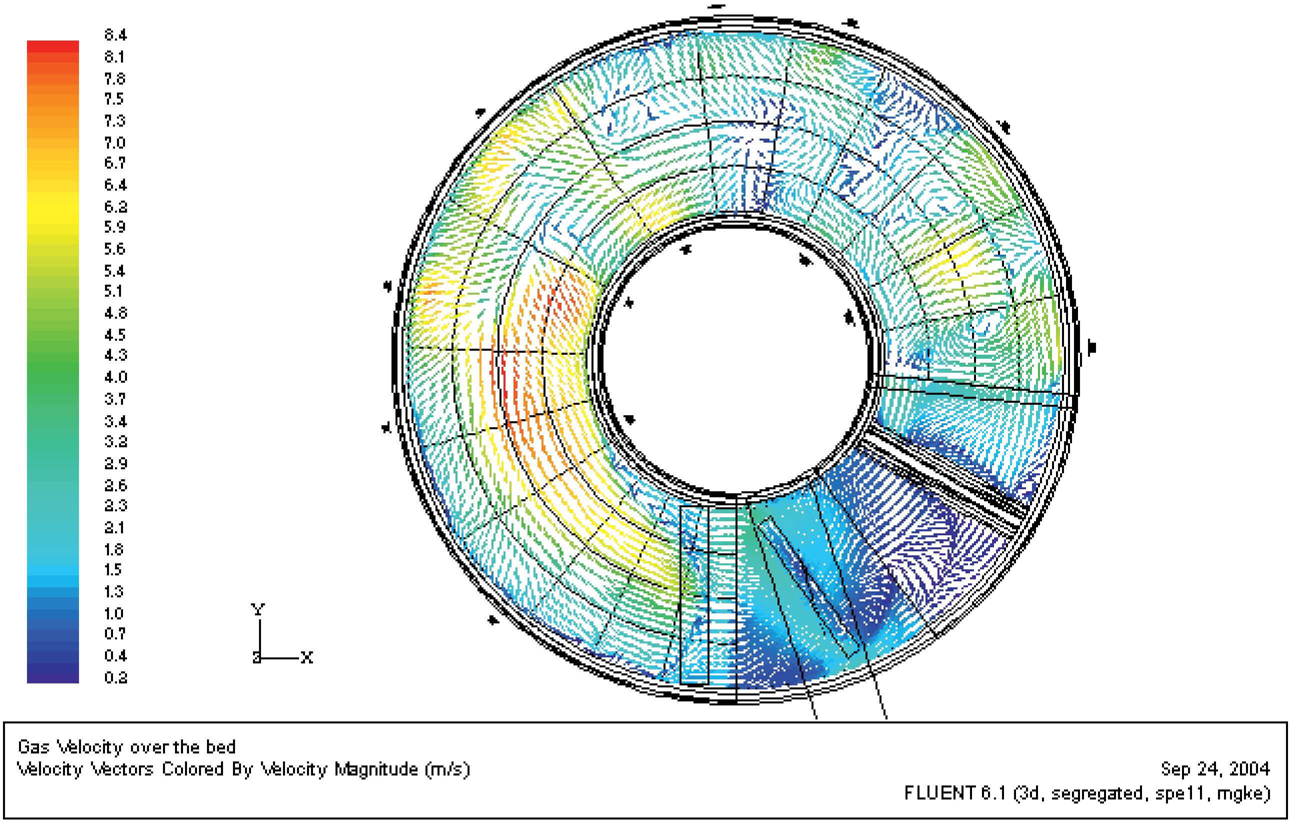


Figure 67. CFD 3-D model - Gas velocities above the bed

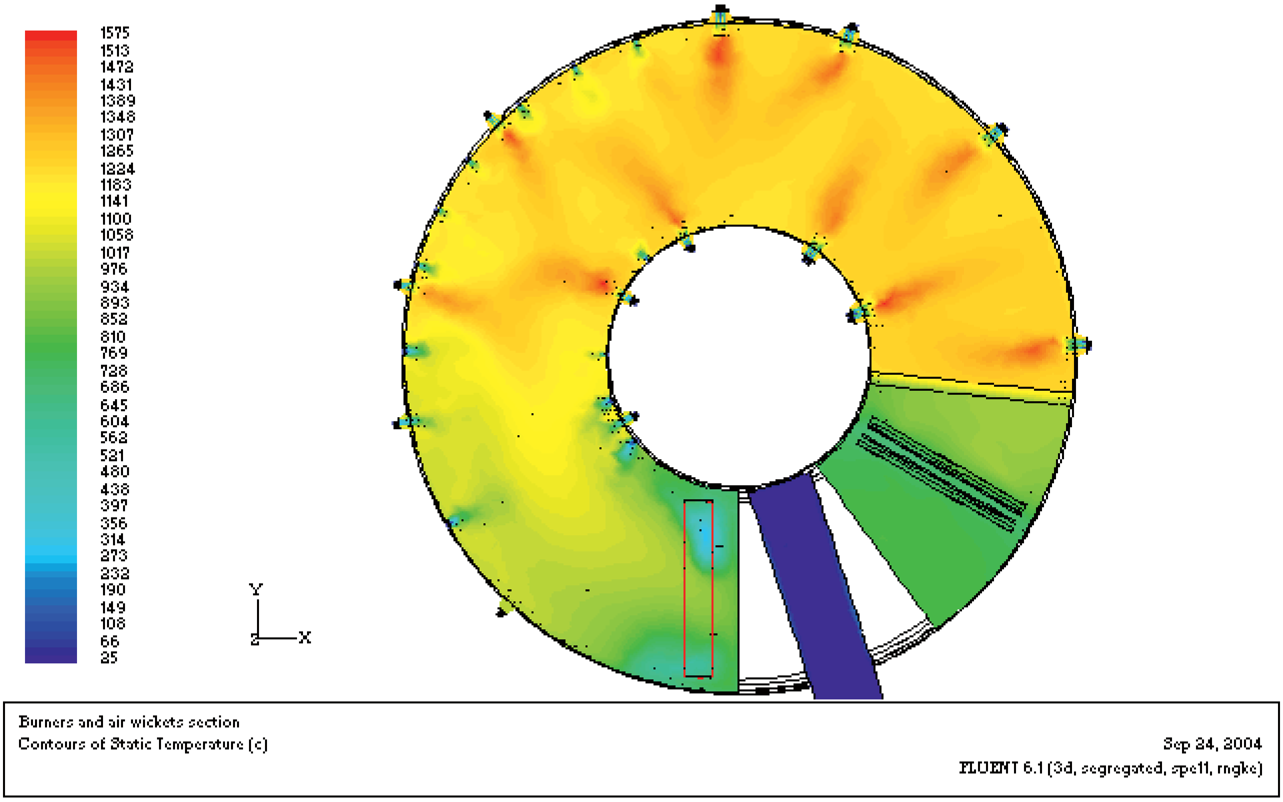


Figure 68. CFD 3-D model - Burners and air wickets cross section - temperatures

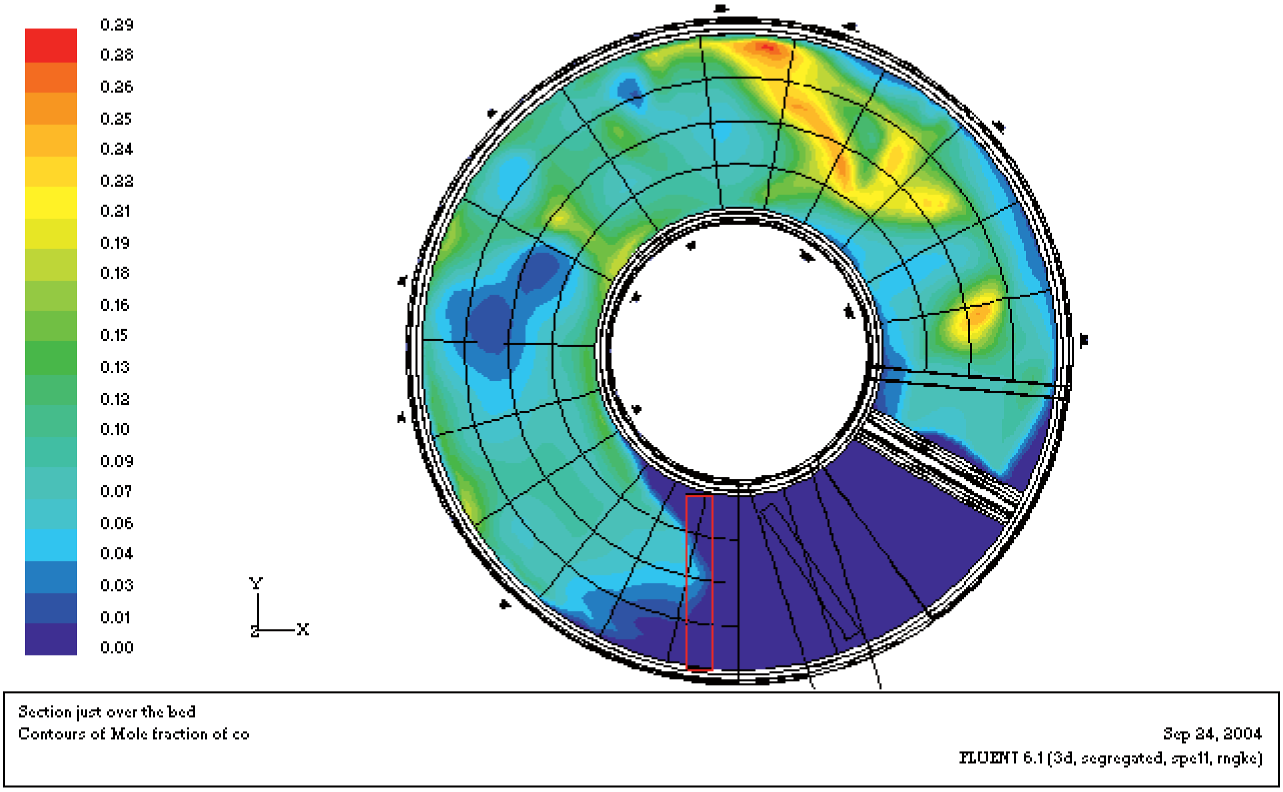


Figure 69. CFD 3-D model - CO fraction above the bed

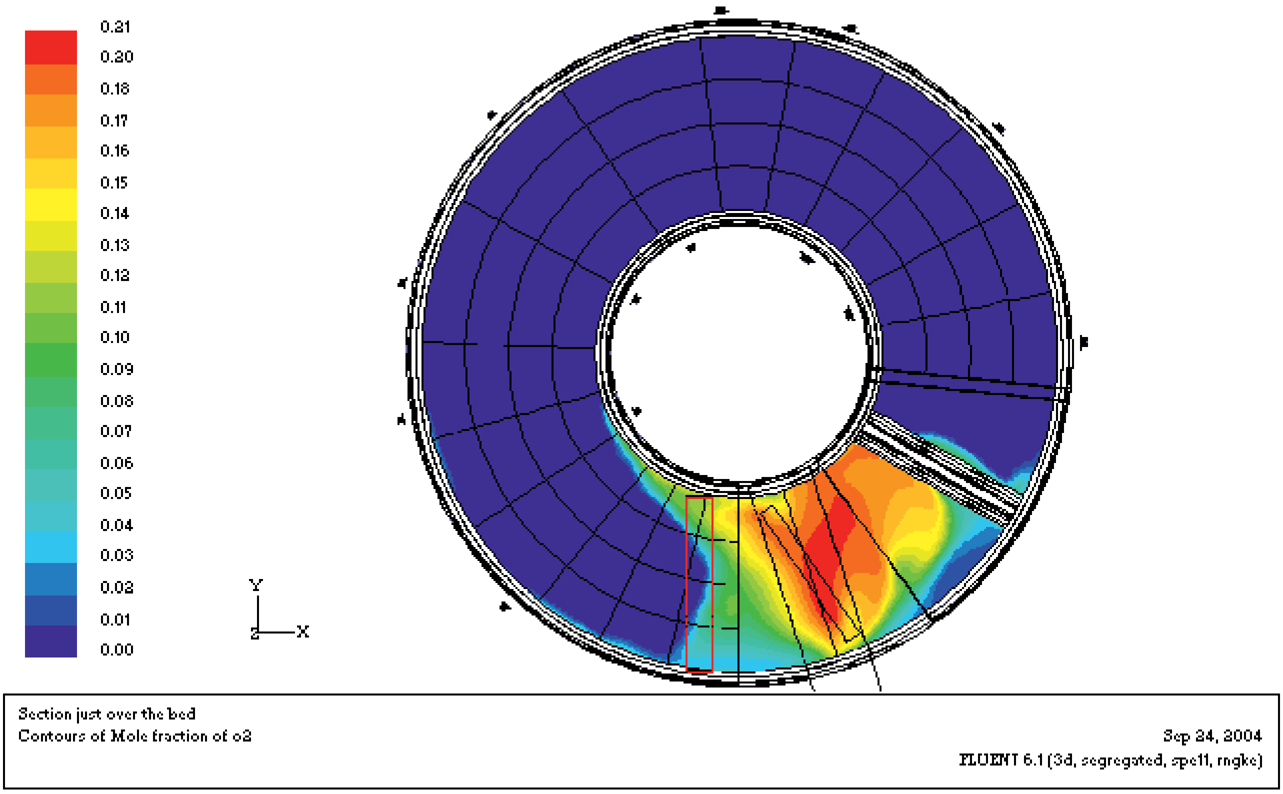


Figure 70. CFD 3-D model - O2 fraction above the bed

2.7 Smelter campaigns – Tests of long duration

2.7.1 Summary

The smelter campaigns have been completed with the tests of long duration, carried out in the period from 01.07.05 to 31.03.06.

The goal of this phase was:

- Definition of plant performances in stable operation, getting conclusive results regarding: process consumptions (coal, oxygen, utilities), productivity, products quality.

As far as the process-related aspects are concerned, the new process may now be considered successfully demonstrated and its observed performances, in terms of efficiency, productivity and flexibility are in fair agreement with the original expectations.

The next logical step to exploit industrially this new technology is a scaled-up project aiming at building and testing a commercial or semi-commercial unit.

2.7.2 Planning of the tests of long duration

As discussed in the final report, the tests of long duration had been originally planned for the mid of 2005. Problems due to the refractory lining forced to postpone the tests, for the reasons detailed in the following.

2.7.2.1 Preliminary tests

Before performing the long duration tests, some preliminary tests have been executed in order to check the operating conditions of the equipment, with special reference to the refractory consumption.

Two tests have been carried out in July 2005:

- *PRELIMINARY TEST OF JULY 2005 N. 1*

This test has been performed in the days from *04.07.05* to *06.07.05*

The DRI produced by RHF has been charged into the smelter on 06.07.05, for a total time of about 240 min.

The main data of this test are collected in the following table.

Parameter	*Unit*	*Value*
Actual DRI charging time into the smelter	*min*	240
Waste treated (dry)	*kg*	8000
DRI charged	*kg*	5300 *
Hot metal produced	*kg*	3400 *
Metal tapping	*n°*	1

* calculated

Table 8: Main working data of the preliminary test of July 2005 n. 1

The analysis of hot metal obtained are the following (% weight):

Hot Metal	*C*	*Mn*	*Si*	*Cr*	*Ni*	*Cu*	*P*	*S*
At tapping	3.50	0.05	0.13	0.19	0.026	0.030	0.058	0.426
In hearth (after empting)	4.02	0.07	0.15	0.28	0.026	0.07	0.063	0.437

Table 9: Hot metal analysis of the preliminary test of July 2005 n. 1

➢ *PRELIMINARY TEST OF JULY 2005 N. 2*

This test has been performed in the days from *27.07.05* to *28.07.05*

The DRI produced by RHF has been charged into the smelter on 28.07.05, for a total time of about 180 min.

The main data of this test are collected in the following table.

Parameter	*Unit*	*Value*
Actual DRI charging time into the smelter	*min*	180
Waste treated (dry)	*kg*	12000
DRI charged	*kg*	7900 *
Hot metal produced	*kg*	5100 *
Metal tapping	*n°*	2

* calculated

Table 10: Main working data of the preliminary test of July 2005 n. 2

The analysis of hot metal obtained are the following (% weight):

Hot Metal	*C*	*Mn*	*Si*	*Cr*	*Ni*	*Cu*	*P*	*S*
1° tapping	2.13	0.06	0.06	0.13	0.020	0.032	0.115	0.430
2° tapping	3.30	0.11	0.06	0.23	0.018	0.028	0.108	0325
In hearth (after empting)	3.93	0.09	1.09	0.47	0.018	0.042	0.120	0.357

Table 11: Hot metal analysis of the preliminary test of July 2005 n. 2

The feeding rate in this second preliminary test has been increased to 3 t DRI / h.

In both the preliminary tests the content of Cr in hot metal and Al_2O_3 in slag have shown a high consumption of refractory lining.

2.7.2.2 Operating conditions of the long duration tests

The long duration tests have been scheduled for lasting a minimum of 7 days.

The organization for those tests has involved the following main aspects:

Personnel

All the personnel on the plant have been foreseen operating on three shifts.

The following personnel has been provided for each shift:

- One responsible
- One process supervisor
- One control room supervisor
- One mechanical supervisor
- One electrical/instrumentation supervisor
- Two chief-operators
- Four operators

Raw materials and utilities

The raw materials (Blast Furnace Dust and Steelmaking Dust) have to be fed also during the test, because the storage bins have a capacity of only 1-2 days.

A pressurized truck must be at disposal for feeding the raw materials for all test lasting.

Also the oxygen tanks have to be refilled, according to the consumption.

Handling of production

The hot metal produced cannot be evacuated continuously, with the lay-out solution foreseen for the pilot plant.

For this reason, the only possibility to handle the hot metal produced, during a test of 7 days and more, is to prepare sand pits, large enough to receive the whole production of liquid metal. After the completion of the trial the hot metal is taken off by crane.

For withdrawing the slag getting out continuously from the smelter, a front-end loader has been placed, for all the test time, in a proper position to collect directly the slag.

The same front loader takes the DRI discharged on ground, when the RHF is not connected with the smelter (mainly during metal tapping).

2.7.2.3 1° long duration test of October 2005

2.7.2.3.1 Main working data

The first long duration test was scheduled in the period from *13.10.05* to *19.10.05*.

Due to problems consequent to the logistics and environmental conditions during hot metal tapping, the hot metal production had to be been limited to the days *17.10.05* and *18.10.05*.

The main characteristics of the test are reported in the following table:

Parameter	*Unit*	*Value*
Actual DRI charging time into the smelter	*min*	480
Waste treated (dry)	*kg*	36000
DRI charged	*kg*	23800 *
Hot metal produced	*kg*	14850 *
Metal tapping	*n°*	6

* calculated

Table 12: Main working data of the 1° LONG DURATION TEST of October 2005

The charging rate of wastes in RHF has been 4 t/h for 6 hours and 6 t/h for 2 hours.

This last value corresponds to a charging rate of about *4.5 t/h of DRI*.

The final analysis of hot metal obtained, during this test, are the following (% weight):

Hot Metal	*C*	*Mn*	*Si*	*Cr*	*Ni*	*Cu*	*P*	*S*
5° tapping	4.41	0.10	0.09	0.32	0.027	0.037	0.089	0.445
6° tapping	4.78	0.12	1.30	0.51	0.026	0.032	0.112	0.727
In hearth (after empting)	4.30	0.09	0.32	0.70	0.031	0.042	0.129	0.365

Table 13: Hot metal analysis of the 1° LONG DURATION TEST of October 2005

2.7.2.3.2 Mass and energy balance

Steady operation period

PRODUCTIVITY & CONSUMPTION

	kg/h	kg/t HM	
Hot Metal	2768.87	1000.00	
Slag	1208.85	436.59	
Waste Gas	2706.66	977.53	
Losses	26.70	9.64	
Total output	6711.09	2423.76	
DRI	4028.57	1454.95	
Metal	5.14	1.86	
Fluxes	0.00	0.00	
Moisture	2.29	0.83	
Coal injected	762.86	275.51	
Coke charged	0.00	0.00	
Oxygen	942.54	340.40	
Metal in vessel	0	0.00	
Slag in vessel	0	0.00	
Coal in vessel	0	0.00	
Coke in vessel	0	0.00	
Nitrogen	508.02	183.47	
Air	321.67	116.17	
Refractory	140.00	50.56	
Total input	6711.09	2423.76	
Actual oxygen consumption		238.43	Nm3/t HM
Actual coal consumption		261.74	kg/t HM
Total oxygen charged		404.76	Nm3/t HM
Total carbon charged		290.49	kg/t HM

Table 14: Productivity and consumption of stable operation period of the 1° LONG DURATION TEST of October 2005

OVERALL ENERGY BALANCE

	kJ/h	%	MW
Energy from combustion	8397204	49.18	2.33
Enthalpy of existing metal+slag	0	0.00	0.00
Energy from post-combustion	4892948	28.66	1.36
Enthalpy of DRI	3783462	22.16	1.05
Total input	17073614	100.00	4.74
Energy for reduction	5008870	29.34	1.39
Enthalpy of metal+slag	6101546	35.74	1.69
Enthalpy of waste gas	4012822	23.50	1.11
Losses	1950376	11.42	0.54
Total output	17073614	100.00	4.74

Table 15: Overall energy balance of stable operation period of the 1° LONG DURATION TEST of October 2005

SUMMARY OF REACTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Energy from reactions	0.94	28.52	3388334
Enthalpy of existing metal+slag	0.00	0.00	0
Energy from post-combustion	1.31	39.64	4710663
Enthalpy of DRI	1.05	31.84	3783462
Total input	3.30	100.00	11882458
Enthalpy of metal+slag	1.69	51.35	6101546
Enthalpy of waste gas	1.46	44.19	5250400
Losses (from the water cooled boxes)	0.14	4.23	502440
Losses (from the bottom)	0.01	0.24	28072
Total output	3.30	100.00	11882458

Table 16: Reaction zone energy balance of stable operation period of the 1° LONG DURATION TEST of October 2005

SUMMARY OF POST-COMBUSTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Enthalpy of gas from reaction zone	1.46	96.64	5250400
Energy from post-combustion	0.05	3.36	182286
Total input	1.51	100.00	5432686
Waste gas enthalpy at the roof exit	1.11	73.86	4012822
Losses in roof	0.36	23.74	1289596
Losses in upper part of vessel	0.04	2.40	130268
Total output	1.51	100.00	5432686

Table 17: Post-combustion zone energy balance of stable operation period of the 1° LONG DURATION TEST of October 2005

2.7.2.3.3 Main results

The main results of the 1° Long Duration Test can be summarized as following:

- The smelter is able to work continuously with a charging rate of 4.5 t/h of DRI, as designed. The margin for increasing post-combustion oxygen flow rate suggests the potential for reaching higher productivity

- The process can start without the presence of a "mother" liquid bath (pre-melted iron), whith consequent higher flexibility in operation.

- It is possible to obtain consistently high C-containing iron

- The refractory (castable) consumption was very high

Picture 7: Hot metal tapping

2.7.2.4 2° long duration test of February 2006

2.7.2.4.1 Main working data

The second long duration test was postponed, in consequence of the necessity to relining the smelter, due the excessive wearing of the refractory utilized.

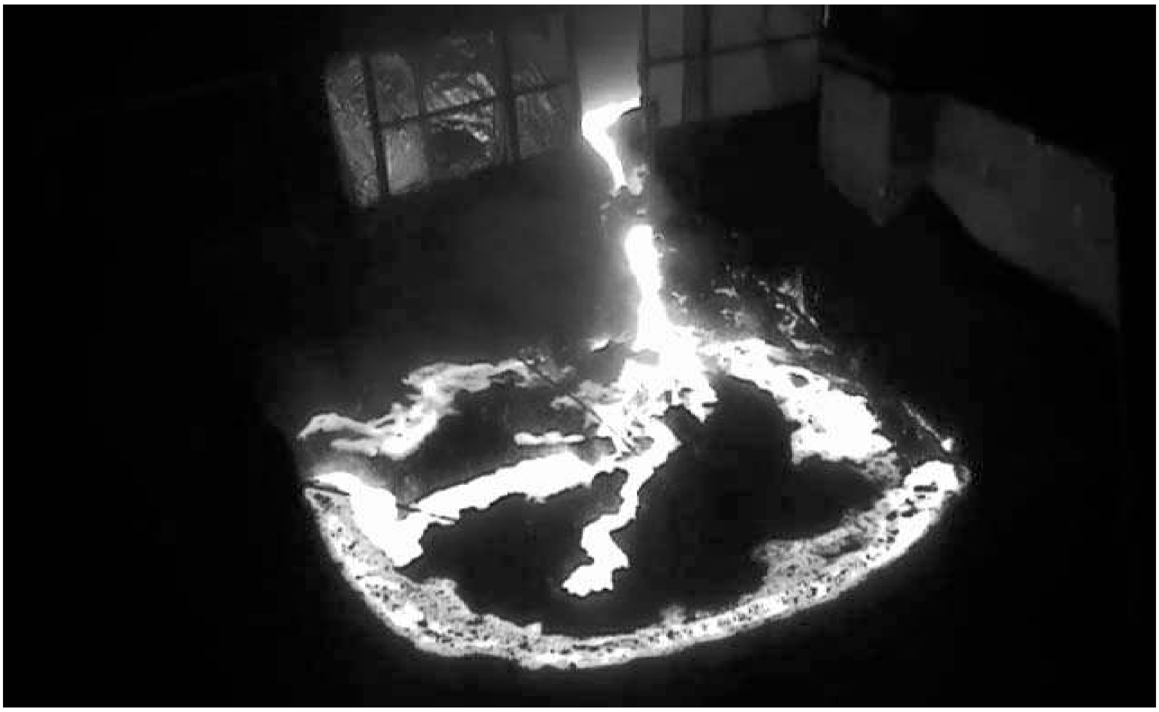
Even if the technically preferred solution is to adopt a different lining concept (based on pre-shaped bricks) it was decided to use castable again in order to reduce the time of supply and installation of the new lining.
In agreement with a well reputed refractory manufacturer, it was decided to install an innovative castable material promising a very good resistance to chemical attak. The new relining was completed before the end of December 2005, but during the drying procedure severe cracks and spalling took place. It was concluded that this material, due to its very low porosity, could not be dried according to standard drying methods for castables. For this reason all the relining was demolished and a new type of castable was utilized for the complete relining.

All these inconveniences forced the programme to shift of about three months.

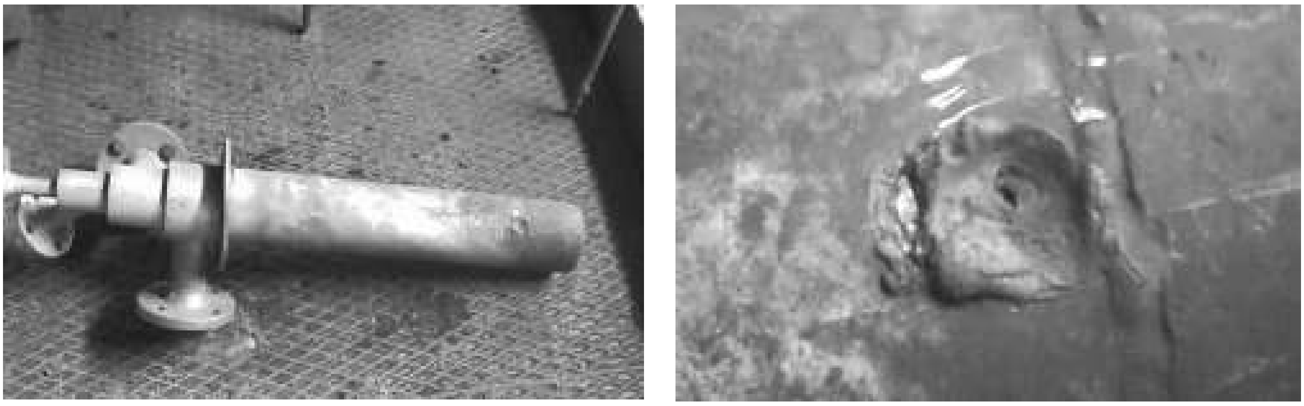
The first long duration test was scheduled in the period from *23.02.06* to *02.03.06*.

On *25.02.06* the metal vessel reached temperature in the order of 200-250 °C, in two points under the post-combustion lances; for this reason it was decided to stop the oxygen blowing through post-combustion lances and *test went on with the primary oxygen injection lances only*.

The test was stopped on *26.02.06* due the detection of a water leakage inside the shell at the low hearth level, with potential risk. After the complete shut down of the furnace, the failure of one of the coal-oxygen lances (see pictures in Fig. 3) was identified as the cause for this leakage.



Picture 8: Hot metal tapping in a deep sand pit



Picture 9: Failed oxy-coal lance. The failure is in the steel-copper seal area

The main working data of the test are reported in the following table:

Parameter	*Unit*	*Value*
Actual DRI charging time into the smelter	*min*	1920
Waste treated (dry)	*kg*	128000
DRI charged	*kg*	85000 *
Hot metal produced	*kg*	52800 *
Tapping	*n°*	18

* calculated

Table 18: Main working data of the 2° LONG DURATION TEST of February 2006

The final analysis of hot metal obtained, during this test, are the following (% weight):

Hot Metal	*C*	*Mn*	*Si*	*Cr*	*Ni*	*Cu*	*P*	*S*
3° tapping	3.00	0.06	0.59	0.14	0.033	0.025	0.128	0.330
5° tapping	2.35	0.07	0.13	0.09	0.033	0.026	0.060	0.360
10° tapping	3.23	0.04	0.01	0.06	0.030	0.029	0.044	0.410
13° tapping	3.38	0.10	0.01	0.064	0.030	0.031	0.043	0.325
16° tapping	3.02	0.10	0.04	0.062	0.030	0.030	0.053	0.360

Table 19: Hot metal analysis of the 2° LONG DURATION TEST of February 2006

2.7.2.4.2 Mass and energy balance

1° Steady operation period

PRODUCTIVITY & CONSUMPTION

	kg/h	kg/t HM	
Hot Metal	1653.88	1000.00	
Slag	934.63	565.11	
Waste Gas	2491.50	1506.46	
Losses	19.55	11.82	
Total output	5099.56	3083.39	
DRI	2647.06	1600.51	
Metal	0.00	0.00	
Fluxes	95.29	57.62	
Moisture	2.46	1.49	
Coal injected	501.18	303.03	
Coke charged	0.00	0.00	
Oxygen	810.13	489.83	
Metal in vessel	0	0.00	
Slag in vessel	0	0.00	
Coal in vessel	0	0.00	
Coke in vessel	0	0.00	
Nitrogen	631.77	381.99	
Air	321.67	194.50	
Refractory	90.00	54.42	
Total input	5099.56	3083.39	
Actual oxygen consumption		343.10	Nm3/t HM
Actual coal consumption		287.88	kg/t HM
Total oxygen charged		518.62	Nm3/t HM
Total carbon charged		386.17	kg/t HM

Table 20: Productivity and consumption of 1° steady operation period of the 2° LONG DURATION TEST of February 2006

OVERALL ENERGY BALANCE			
	kJ/h	%	MW
Energy from combustion	5300108	45.22	1.47
Enthalpy of existing metal+slag	0	0.00	0.00
Energy from post-combustion	4080039	34.81	1.13
Enthalpy of DRI	2341280	19.97	0.65
Total input	11721428	100.00	3.26
Energy for reduction	1826867	15.59	0.51
Enthalpy of metal+slag	4036834	34.44	1.12
Enthalpy of waste gas	2923406	24.94	0.81
Losses	2934321	25.03	0.82
Total output	11721428	100.00	3.26

Table 21: Overall energy balance of 1° steady operation period of the 2° LONG DURATION TEST of February 2006

SUMMARY OF REACTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Energy from reactions	0.96	36.91	3473241
Enthalpy of existing metal+slag	0.00	0.00	0
Energy from post-combustion	1.00	38.22	3596633
Enthalpy of DRI	0.65	24.88	2341280
Total input	2.61	100.00	9411154
Enthalpy of metal+slag	1.12	42.89	4036834
Enthalpy of waste gas	1.39	53.03	4990353
Losses (from the water cooled boxes)	0.10	3.78	355895
Losses (from the bottom)	0.01	0.30	28072
Total output	2.61	100.00	9411154

Table 22: Reaction zone energy balance of 1° steady operation period of the 2° LONG DURATION TEST of February 2006

SUMMARY OF POST-COMBUSTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Enthalpy of gas from reaction zone	1.39	91.17	4990353
Energy from post-combustion	0.13	8.83	483406
Total input	1.52	100.00	5473760
Waste gas enthalpy at the roof exit	0.81	53.41	2923406
Losses in roof	0.67	44.21	2420086
Losses in upper part of vessel	0.04	2.38	130268
Total output	1.52	100.00	5473760

Table 23: Post-combustion zone energy balance of 1° steady operation period of the 2° LONG DURATION TEST of February 2006

2° Steady operation period

PRODUCTIVITY & CONSUMPTION			
	kg/h	kg/t HM	
Hot Metal	1625.99	1000.00	
Slag	857.78	527.54	
Waste Gas	2437.49	1499.09	
Losses	15.47	9.52	
Total output	4936.73	3036.15	
DRI	2680.65	1648.63	
Metal	0.00	0.00	
Fluxes	94.35	58.03	
Moisture	2.13	1.31	
Coal injected	396.77	244.02	
Coke charged	0.00	0.00	
Oxygen	779.65	479.49	
Metal in vessel	0	0.00	
Slag in vessel	0	0.00	
Coal in vessel	0	0.00	
Coke in vessel	0	0.00	
Nitrogen	631.50	388.38	
Air	321.67	197.83	
Refractory	30.00	18.45	
Total input	4936.73	3036.15	
Actual oxygen consumption		335.86	Nm3/t HM
Actual coal consumption		231.82	kg/t HM
Total oxygen charged		497.43	Nm3/t HM
Total carbon charged		395.92	kg/t HM

Table 24: Productivity and consumption of 2° steady operation period of the 2° LONG DURATION TEST of February 2006

OVERALL ENERGY BALANCE	kJ/h	%	MW
Energy from combustion	5734350	51.25	1.59
Enthalpy of existing metal+slag	0	0.00	0.00
Energy from post-combustion	3042562	27.19	0.85
Enthalpy of DRI	2411304	21.55	0.67
Total input	11188216	100.00	3.11
Energy for reduction	1629701	14.57	0.45
Enthalpy of metal+slag	3853476	34.44	1.07
Enthalpy of waste gas	2925637	26.15	0.81
Losses	2779402	24.84	0.77
Total output	11188216	100.00	3.11

Table 25: Overall energy balance of 2° steady operation period of the 2° LONG DURATION TEST of February 2006

SUMMARY OF REACTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Energy from reactions	1.14	44.13	4104649
Enthalpy of existing metal+slag	0.00	0.00	0
Energy from post-combustion	0.77	29.95	2785846
Enthalpy of DRI	0.67	25.92	2411304
Total input	2.58	100.00	9301799
Enthalpy of metal+slag	1.07	41.43	3853476
Enthalpy of waste gas	1.36	52.64	4896876
Losses (from the water cooled boxes)	0.15	5.63	523375
Losses (from the bottom)	0.01	0.30	28072
Total output	2.58	100.00	9301799

Table 26: Reaction zone energy balance of 2° steady operation period of the 2° LONG DURATION TEST of February 2006

SUMMARY OF POST-COMBUSTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Enthalpy of gas from reaction zone	1.36	95.02	4896876
Energy from post-combustion	0.07	4.98	256716
Total input	1.43	100.00	5153592
Waste gas enthalpy at the roof exit	0.81	56.77	2925637
Losses in roof	0.58	40.70	2097687
Losses in upper part of vessel	0.04	2.53	130268
Total output	1.43	100.00	5153592

Table 27: Post-combustion zone energy balance of 2° steady operation period of the 2° LONG DURATION TEST of February 2006

3° Steady operation period

PRODUCTIVITY & CONSUMPTION			
	kg/h	kg/t HM	
Hot Metal	1749.42	1000.00	
Slag	795.87	454.93	
Waste Gas	2739.51	1565.95	
Losses	22.29	12.74	
Total output	5307.08	3033.62	
DRI	2619.05	1497.09	
Metal	0.00	0.00	
Fluxes	109.52	62.61	
Moisture	2.81	1.61	
Coal injected	571.43	326.64	
Coke charged	0.00	0.00	
Oxygen	895.15	511.69	
Metal in vessel	0	0.00	
Slag in vessel	0	0.00	
Coal in vessel	0	0.00	
Coke in vessel	0	0.00	
Nitrogen	757.44	432.97	
Air	321.67	183.87	
Refractory	30.00	17.15	
Total input	5307.08	3033.62	
Actual oxygen consumption		358.40	Nm3/t HM
Actual coal consumption		310.31	kg/t HM
Total oxygen charged		516.07	Nm3/t HM
Total carbon charged		376.19	kg/t HM

Table 28: Productivity and consumption of 3° steady operation period of the 2° LONG DURATION TEST of February 2006

OVERALL ENERGY BALANCE	kJ/h	%	MW
Energy from combustion	10664939	78.16	2.96
Enthalpy of existing metal+slag	0	0.00	0.00
Energy from post-combustion	706575	5.18	0.20
Enthalpy of DRI	2273149	16.66	0.63
Total input	13644664	100.00	3.79
Energy for reduction	2245424	16.46	0.62
Enthalpy of metal+slag	4105522	30.09	1.14
Enthalpy of waste gas	4646465	34.05	1.29
Losses	2647253	19.40	0.74
Total output	13644664	100.00	3.79

Table 29: Overall energy balance of 3° steady operation period of the 2° LONG DURATION TEST of February 2006

SUMMARY OF REACTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Energy from reactions	2.34	78.30	8419515
Enthalpy of existing metal+slag	0.00	0.00	0
Energy from post-combustion	0.02	0.56	60149
Enthalpy of DRI	0.63	21.14	2273149
Total input	2.99	100.00	10752813
Enthalpy of metal+slag	1.14	38.18	4105522
Enthalpy of waste gas	1.70	57.07	6136190
Losses (from the water cooled boxes)	0.13	4.48	481505
Losses (from the bottom)	0.01	0.28	29597
Total output	2.99	100.00	10752813

Table 30: Reaction zone energy balance of 3° steady operation period of the 2° LONG DURATION TEST of February 2006

SUMMARY OF POST-COMBUSTION ZONE ENERGY BALANCE

	MW	%	kJ/h
Enthalpy of gas from reaction zone	1.70	90.47	6136190
Energy from post-combustion	0.18	9.53	646426
Total input	1.88	100.00	6782617
Waste gas enthalpy at the roof exit	1.29	68.51	4646465
Losses in roof	0.55	29.45	1997199
Losses in upper part of vessel	0.04	2.05	138952
Total output	1.88	100.00	6782617

Table 31: Post-combustion zone energy balance of 3° steady operation period of the 2° LONG DURATION TEST of February 2006

2.7.2.4.3 Main results

The main results of the 2° Long Duration Test can be summarized as following:

- The smelter can work steadily for relatively long periods, with process parameters very close to their theoretical design values

- Continuous or semi-continuous slag tapping from its dedicated hole was always implemented during normal operation (see picture in Fig. 4). In this way, the slag level and the maximum metal level were controlled efficiently. However, some entrainment of DRI and coal in slag was observed. The original syphon system (not feasible on such small scale unit) would have avoided this problem

Picture 10: Continuous slag tapping from slag taphole

- As compared to previous tests, interruptions of DRI feeding were much more limited, basically only during metal casting (see fig. 5). After taphole gunning, process restarts much quicker when DRI feeding is restored immediately together with coal and oxygen blowing. If a drilling machine would be used instead of oxygen opening, the DRI feeding as well as the blowing process could be uninterrupted.

- It was also shown the possibility to work without post-combustion, increasingly consequently the primary oxygen flow rate. However this operational method resulted in a loss of flexibility and a slower restart of the process after a delay.

- Operating for a longer period, in stable conditions, the wearing of refractory lining decreased in a very significant way, even if the consumption rate is still too high to be industrially acceptable.

Picture 11: Opening of the hot metal taphole while hot DRI is deviated to slag pit

2.7.3 Conclusions

2.7.3.1 Productivity and consumption parameters

The long duration tests provided an important set of data to evaluate performance figures related to productivity and consumptions; of course, due to the size of the plant and to its operational limitations, some figures must be considered as preliminary and are subject to a more precise evaluation during future development stages.

A production rate of 2.8 t/h of hot metal has been practically reached, that means (with a hearth surface of about 0.9 m2) *a productivity more than 3 t/h/m2.*

For the higher production rate, injected coal consumption was approx. 250 kg/t H.M., with a slag production of 400 ÷ 500 kg/t H.M. and a very high cooling intensity.
The corresponding total carbon rate was approx. 300 kg/t H.M., out of which about 200 kg from injection lances and about 100 kg charged with DRI. A 5%-10% of carbon losses (by gas and slag carryover) has been estimated.

The oxygen consumption was 300 ÷ 350 Nm3/t H.M. for the productivity of 3 t H.M./h.

2.7.3.2 Product characteristics

The hot metal produced can be close to C saturation, when the process runs at higher temperature; otherwise it is possible obtaining a metal with 3 ÷ 4 % of C.

For operating reasons (dosing difficulties), it was not possible to inject pulverized lime, mixed with coal, as foreseen in the original design. As a consequence of that, *the content of sulphur in hot metal was always high, never less than 0.3 % with a slag/metal partition factor below 10.*

2.7.3.3 Operating features

The DRI charging from the top of the smelting vessel, at high temperature, involves some key-points, which are peculiar for the running of the NST smelting process.

The main operating benefits are the following:

- Smelting can start without a pre-existing liquid bath
- The process can operated in a wide range of productivity from 30% to the nominal productivity

Additional operating aspects are:

- It is possible to take the process in stand-by, with a reduced rate of injection of oxygen and coal
- Metal tapping schedule may be controlled on the basis of simple Fe balance and/or by observation of first metal appearance in slag.
- Process thermal control was improved by measuring systematically slag temperature at the taphole. A relatively constant difference has been observed between such pyrometric values and bath temperature in the hearth.

2.7.3.4 Main outstanding problems

The two main aspects to face during the further development stage are:

- Selection of a refractory lining and a cooling system able to reduce the refractory consumption to reasonable low value
- Handling of liquid metal and slag, in order to obtain a sufficient separation of the two phases

Other points to be further investigated are:

- Dust carryover and means to minimize it
- Metal desulfurisation
- FeO in slag and relevant Fe yield
- Improvements in design of coal-oxygen lances and other equipment.

3 Bibliography - References

During the first stage of the project a literature survey was carried out, which summarised an overview of different iron making processes, which had been developed during the last decades and also included in-house knowledge and background information.

The documentation resulting from the survey was presented to the Commission during the T1 meeting held in Brussels in April 2003.

From the investigation it was clear that during the development phase the so-called “Inbath Processes” (like Redsmelt NST is) reported critical areas such as:

- refractory life
- lance life
- post combustion degree
- heat transfer into the bath
- carry over of DRI with the off-gas stream

During the basic engineering of the project some of the information collected, especially referred to the critical areas, were used for the internal discussion studies.

Glossary

BF	Blast Furnace
BOF	Basic Oxygen Furnace
DRI	Direct Reduced Iron
HM	Hot Metal
NST	New Smelting Technology
RHF	Rotary Hearth Furnace
w.b.	wet basis

APPENDIX

ANNEX I OF THE CONTRACT

Contract N°: 7215-PA/PB/060
Reference N°: 01-T1.02a,b
PP N°: PP408

TITLE: Direct Ironmaking via Rotary Hearth Furnace and New Smelting Technology

1. OBJECTIVES

The aim of this demonstration project is to develop and test a new two-step iron making process based on:

- Iron bearing materials reduction in a Rotary Hearth Furnace (RHF)
- Smelting of hot prereduced iron in a coal and oxygen blown Converter

This process matches the demand of high purity " Steel Scrap Substitutes " in the mid-size production range, between 0.3 and 1,5 million tons per year, typical of Mini Mills.

The here proposed solutions are based on the recent experiences gained at the laboratory and pilot scale on RHF and Smelter plants/processes.

Further objectives of the project are:

- verify the productivity and reliability of the plant, by producing a quantity of hot metal enough to provide experimental results directly transferable to the commercial size

- develop techniques to avoid polluting emissions in a process that utilises waste materials from iron/steel making integrated plants

- develop oxygen / coal blowing and hot DRI charging techniques for optimum smelting and for hot metal pre-refining inside the Smelter

2. WORK PROGRAMME AND DISTRIBUTION OF TASKS

2.1 Work Programme

The work of the project is devoted to the design, construction and operation of a demonstration plant (hereinafter referred to as the plant).

The plant is composed of two main units:

- Rotary Hearth Furnace (RHF)
- Smelter

and the relevant auxiliaries:

- Raw Material Preparation (storage, dosing, transportation, mixing, pelletizing)
- Cooling System (for RHF and smelter units)
- Off-gas System (for RHF and smelter units)
- Instrumentation and control system (for RHF and smelter units)
- Hot DRI charging system (for smelter unit)
- etc.

The main technical data of the Rotary Hearth Furnace are:

DRI production:	4 ÷ 6	t/h
RHF dimensions:		
Wall to wall diameter:	11	m
Hearth width (useful):	3	m
Total Hearth Surface:	70	m^2

The main technical data of the smelter are:

Target hot metal production:	3 ÷ 5	t/h
Smelter dimensions:		
Diameter (inner):	1.5	m
Height:	3.5	m

The smelter is a fixed-type vessel.
Cooling of the vessel will be performed by:

- copper staves or panels in the most stressed areas (slag zone)
- steel panels for the rest of the vessel

The injection system will be composed of:

- a vertical top charging pipe for hot DRI injection (the charging is performed mainly by gravity)
- a lower level of side lances for oxygen and coal injection. The additives will be injected with coal.
- an upper level of side lances for secondary oxygen injection (to promote post-combustion in transition zone)

During the project the following tasks will be performed.

Task 1 – Design and construction of the plant

Sub Task 1.1 - Basic Engineering of the plant

- Preliminary lab tests
- Basic process and structural calculations
- Equipment data sheets
- Quantified flow diagrams
- Lay out drawings
- Basic functional descriptions
- One-line electrical diagrams
- P&I diagrams
- Equipment, motor and sensor lists

Sub Task 1.2 - Detail Engineering of the plant

- Process and structural final calculations
- Drawings for manufacturing / assembly
- Drawings for erection
- Purchasing technical specifications (final)
- Detail functional descriptions
- Operations and maintenance manuals
- Control system software

Sub Task 1.3 - Construction

- Workshop Engineering and Manufacturing

Task 2 – Delivery and Erection of the plant

Sub Task 2.1 - Delivery (to site)

- Shipment of materials and equipment to Lucchini works in Piombino

Sub Task 2.2 – Erection

- Installation of equipment and on-site building of RHF, smelter and auxiliaries

Task 3 – Start-up and hot tests

Sub Task 3.1 – Cold Tests and Start-Up

- Checking of parts and components of the RHF, smelter and auxiliaries (pipes, valves, pumps, burners, etc.)

Sub Task 3.2 – RHF Tests

- Hot tests using standard iron ore / coal blends for checking the pre-reduction unit
- Hot tests using typical waste blends of integrated iron and steel plant, to produce DRI continuously

Sub Task 3.3 – Smelter Tests

- Hot tests using hot metal from blast furnace and cold metallic charge to set-up the smelting equipment and relevant operating practices. In particular the following practices will be tested and established:

    - Start-up and shut-down procedures
    - Tapping procedures

Task 4 - Plant Operation (PHASE I)

During this phase it is foreseen to operate tests of short duration. The typical trial will be run for a period of one shift (eight hours).
This phase is dedicated to the assessment and optimisation of the process.
The staff involved in the tests will be supported by the control system (instrumentation, basic automation and computer control).

The main factors that will be investigated during Rotary Hearth Furnace operation are:

EFFECT OF

- Mixing and balling conditions
- Raw materials and binders used for pellets preparation (chemistry and mix). During the trials at least two different blends of materials will be used (different wastes or same wastes in different ratios)
- RHF operating conditions (mainly temperature and gas composition inside the furnace, residence time)

ON TO

- Green pellets mechanical properties
- DRI metallisation
- DRI chemistry (C, S, Zn, Pb and other minor components)
- DRI mechanical properties, including sticking behaviour at high temperature

The different qualities of hot DRI so produced will be charged continuous-wise into the smelter.
Starting from that, the following main parameters will be studied and tuned in the smelting unit:

EFFECT OF

- Post-combustion
- Blowing conditions (coal/oxygen ratio, pressure and velocity of injection, positioning and inclination of oxygen/coal lances)
- Flux additions (to change slag composition)
- Slag properties (composition, foaming, etc.)

ON TO

- Productivity
- Coal and oxygen consumption
- Hot metal chemistry

The process control algorithms will be defined, implemented and tuned.
A first evaluation of emissions will be performed during these tests.

The plant and its components will be subject to the modifications necessary to optimise the process performance and solve the encountered problems.

The final result of this phase is to define the reference configuration of the plant and the reference operating conditions of the process.

Task 5 - Plant Operation (PHASE II)

During this phase it is foreseen to operate tests of long duration. The typical trial of long duration will be run for a period of one week.
This phase is dedicated to the evaluation of the industrial reliability of the plant and its components.
The plant will be operated in the reference conditions resulting from the PHASE I. The plant will be run under continuous operation, especially to evaluate the industrial reliability of:

- Charging System
- Refractory lining
- Cooling system

Data will be collected systematically to evaluate the environmental aspects and to define the future guidelines to minimise pollutant emissions.

The plant and its components will be subject to the modifications necessary to solve the encountered problems.
The operating and maintenance practices will be defined, implemented and tuned.

At the end of this phase the conditions for the industrial scaling-up of the plant should be clarified and the design methodologies defined.

2.2 Distribution of Tasks

The project is co-ordinated by Lucchini S.p.A. (Italy).

Lucchini S.p.A. will contribute to the project by buying and hosting the demonstration plant in its Piombino Works and by supplying technical staff, operating personnel, maintenance, raw materials, energy, media, laboratory and other field services during the test campaign.
At the end of the project, Lucchini S.p.A. is a potential user of this new technology and will co-operate with SMS Demag in marketing the technology by providing process and operating assistance for future users.

SMS Demag AG (Germany) role in the project will be to assist Lucchini during the plant engineering, erection, commissioning and operation, by providing its technological know-how in reduction and smelting processes.
After the conclusion of the project, SMS Demag will take care of the marketing of this technology and of its further industrial development, always in co-operation with Lucchini.

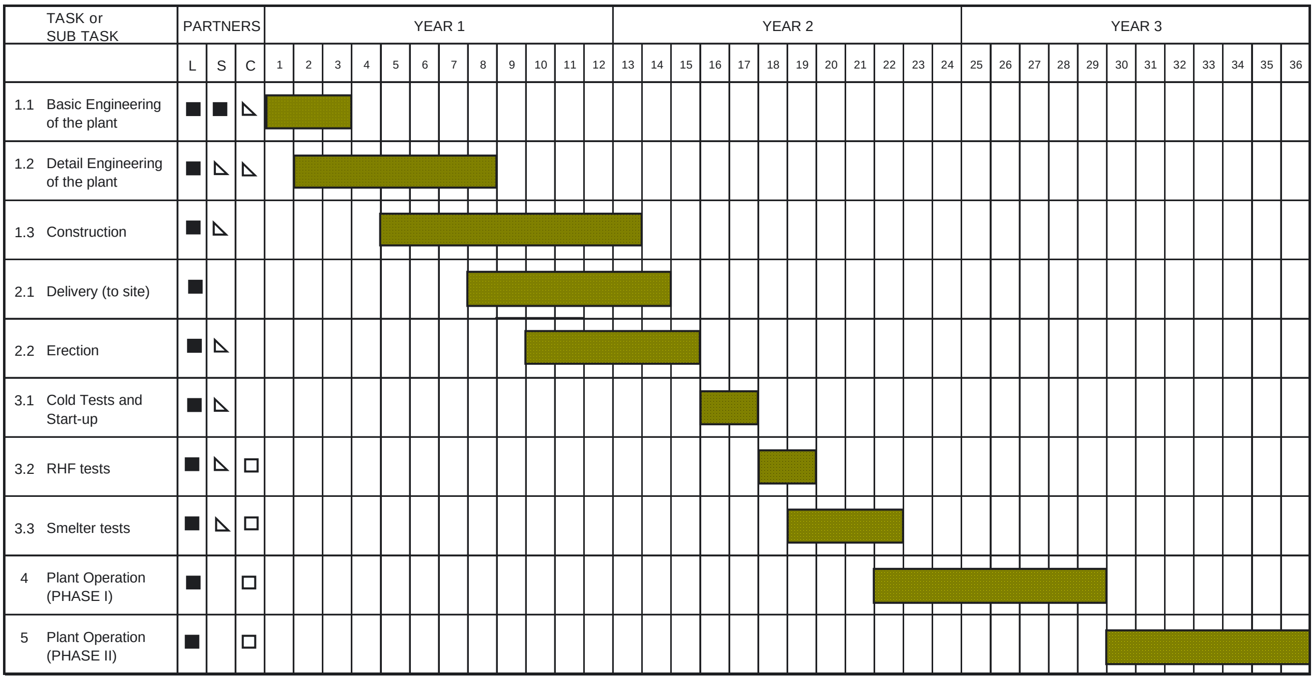
Lucchini S.p.A. and SMS Demag will have CSM S.p.A. (Italy) as subcontractor.

CSM S.p.A. will supply the following services:
- Chemical and technological characterisation of raw materials and products (DRI, slag, metal, waste gas)
- Experimental measurements for the evaluation of environmental aspects of the process

3. *WAYS AND MEANS*

- Know-how for all the technologies involved in the project (raw materials preparation and handling, Rotary Hearth Furnace, smelting unit, etc.)
- Techniques for basic and detail design of all the equipment involved in the plant
- Computer algorithms for basic process calculations
- Computer algorithms for structural calculations
- Know-how for the modellisation of the process
- Area for plant installation made available by Lucchini inside Piombino works
- Mobile equipment for material transportation inside Piombino works
- Batch test furnace for characterisation of RHF operating conditions
- Laboratory equipment for technological and chemical characterisation of raw materials
- Laboratory equipment for technological and chemical characterisation of green pellets
- Laboratory equipment for technological and chemical characterisation of DRI pellets
- Laboratory equipment for chemical characterisation of hot metal
- Laboratory equipment for chemical characterisation of slag
- Field equipment for emissions monitoring

4. *PROGRAMME BAR CHART*



TASK or SUB TASK	PARTNERS			YEAR 1												YEAR 2												YEAR 3											
	L	S	C	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1.1 Basic Engineering of the plant	■	■	◺	▨	▨	▨																																	
1.2 Detail Engineering of the plant	■	◺	◺		▨	▨	▨	▨	▨	▨	▨																												
1.3 Construction	■	◺						▨	▨	▨	▨	▨	▨	▨	▨	▨																							
2.1 Delivery (to site)	■										▨	▨	▨	▨	▨	▨	▨																						
2.2 Erection	■	◺											▨	▨	▨	▨	▨	▨																					
3.1 Cold Tests and Start-up	■	◺																	▨	▨																			
3.2 RHF tests	■	◺	□																		▨	▨																	
3.3 Smelter tests	■	◺	□																			▨	▨	▨	▨														
4 Plant Operation (PHASE I)	■		□																						▨	▨	▨	▨	▨	▨	▨	▨							
5 Plant Operation (PHASE II)	■		□																														▨	▨	▨	▨	▨	▨	▨

L: LUCCHINI
S: SMS DEMAG
C: CSM (Sub-Contractor)

Intensity of presence in the project phase:
■ High
□ Medium
◺ Low

5. *CONTRACTUAL PHRASES*

The results of the project will be the subject of a publication in the “Technical Steel Research“ series.

The research described above will be placed in the area covered by Expert Group: T1 – Iron and Steelmaking.

European Commission

EUR 22826 — Direct ironmaking via rotary hearth furnace and new smelting technology

A. Guglielmini, R. Degel

Luxembourg: Office for Official Publications of the European Communities

2007 — 132 pp. — 21 × 29.7 cm

Technical steel research series

ISBN 92-79-05447-1

ISSN 1018-5593

Price (excluding VAT) in Luxembourg: EUR 25