# IRMA – Flowsheet Model Examples of Application

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ULCOS is a large European research project that aims to identify and develop technology that could enable a drastic reduction in $CO_2$ emissions from ore-based steel production. The IRonMAking flowsheeting model (IRMA) has made a vital contribution to one of the ULCOS subprojects, as IRMA models were used to evaluate the economics and $CO_2$ reduction potential of a large number of alternative ironmaking routes.

IRMA is a software tool that allows for the use of thermodynamic data relevant to iron- and steelmaking in a flowsheeting environment. It was developed by Corus to serve as a dedicated, flexible and accessible tool to evaluate and compare a wide range of ironmaking routes.

IRMA can be used to calculate consumption figures, product quality and the occurrence and significance of emissions. IRMA can do this for a wide range of operating conditions and raw material compositions.

IRMA is currently being used for benchmarking, design and pilot plant development of the ISARNA process, which was developed in the context of the ULCOS project. ISARNA is one of the four process routes that have been selected for further development within ULCOS.

## Introduction

The IRMA process modelling tool was applied in the Ultra Low $CO_2$ Steelmaking (ULCOS) project. ULCOS is a groundbreaking project, supported by the EU and advanced by 48 European companies and institutes, to identify and develop technology that could enable a drastic reduction (50%) in $CO_2$ emissions from ore-based steel production by 2050.

The aim of the first part of ULCOS was to select technologies that have the potential to achieve the ULCOS objective. The ULCOS partners put forward a wide range of processes for evaluation. To facilitate the selection procedure, all processes were categorized into eight subprojects. Four subprojects focussed on process technology, while the other four focussed on supporting technologies. The results from all subprojects were collected and evaluated in detail, which included the $CO_2$ impact.

One of the process technology subprojects focussed on smelting reduction technology. The following processes were evaluated:

- Bath smelting processes, similar to DIOS, HIsmelt [1] and hydrogen plasma [2];
- Moving hearth furnaces in combination with an electric arc furnace (EAF), similar to Redsmelt, Sidcomet and Primus [3];
- Fluidized bed processes in combination with an EAF, similar to Circofer [4];
- Shaft processes, such as OxiCup [5].
- Melting cyclones, similar to CCF [6];

In addition to the usual selection criteria, such as cost and technological performance, the $CO_2$ emissions were an important consideration. It was decided that a single modelling platform was best suited to calculate the consumption figures for this comparison on an agreed and consistent basis.

Since the processes under investigation are based on very different principles, it was decided to use a flowsheeting tool. Apart from solving the heat and mass balances for a process, a flowsheeting tool offers considerable flexibility through the use of a few simple unit operations. Commercially available tools are generally not tailored to the modelling of ironmaking processes. Therefore, Corus started to develop a basic flowsheeting tool dedicated to modelling ironmaking processes, which was named IRMA.

In this paper, the functionality of the modelling tool will be described first. Then a selection of the ULCOS results produced by IRMA will be presented. Finally, the modelling tool will be demonstrated by presenting case studies on the ISARNA and ULCORED processes, followed by conclusions.

## Tool description

In IRMA, a mass balance is set up for each individual chemical element in each individual unit operation. All these individual mass balances are coupled through the streams connecting the unit operations, see for example Figure 2 and Figure 3.

The heat balance in IRMA includes the heat capacities for relevant substances and the enthalpies for a large number of reactions, in the wide temperature range associated with ironmaking. This information is extracted from the thermodynamic database. This database is also used in the unit operation, which is capable of calculating the thermodynamic equilibrium.

A flowsheet model consists of material and energy streams and unit operations that alter these streams. The composition of the input streams is specified by the user. To facilitate the input, IRMA offers a number of standard input materials, such as coal, ore and gas, and allows "user-defined" materials. The input layout for the material streams corresponds with chemical analyses commonly used in ironmaking.

IRMA uses 3 main unit operations: a mixer, a reactor and a separator, which can all be used isothermally or adiabatically. Apart from mixing materials, the mixer can also provide the water-gas shift and thermodynamic equilibrium. The reactor processes user-specified reactions with user-specified conversions. The separator separates a specified amount or fraction of user-specified phases and components.

IRMA subsequently solves the flowsheet through an iterative process, which stops when the difference between the solutions of subsequent iterations drops below a user-specified level. Loop convergence capability speeds up the iterative process. When the iterative process is completed, IRMA produces the composition and size of all intermediate, product and by-product streams.

Fixed linear relations between streams and unit operations can be specified through the use of couplings, for example to enforce the desired hot metal carbon content. Furthermore, the user can provide a set of targets for certain parameters through the use of conditions. IRMA iteratively alters a set of user-specified parameters to attain these targets. Through this procedure, the modelling tool can for example determine how much coal is required to close the heat balance of a process.

Input tables facilitate the variation of the most important process parameters. The model results can be presented in the form of text boxes, which can be exported to other software.

Important limitations of IRMA are that it is steady state and that kinetics need to be supplied to the model.

## Results

IRMA was first validated with a standard blast furnace case. Then IRMA was used to model the three process routes that were continued after the preliminary selection within the ULCOS smelting reduction subproject:

- ISARNA, see "Case study: ISARNA";
- Rotary hearth furnace (RHF) followed by an EAF;
- Fluidized bed (FB) followed by an EAF.

The IRMA models of these process routes were validated by comparing the IRMA results with results obtained with existing models, and by peer review. After validation, the IRMA models were used to calculate the consumption figures for a number of scenarios, where the coal composition was the main variable.

The most relevant results of the IRMA models were used for detailed sustainability and $CO_2$ evaluation. The results of this evaluation are presented in Table 1. This table also shows the results for the application of two support technologies for $CO_2$ reduction, i.e. $CO_2$ capture and storage (CCS) and replacement of fossil fuels by biomass. In the table, 100% represents the blast furnace reference energy consumption and $CO_2$ emission.

ISARNA is the only route that uses less primary energy than the blast furnace. Nonetheless, all process routes can reach a significant reduction in $CO_2$ emission, especially if support technologies are applied. The RHF and FB routes reduce their $CO_2$ emission through the replacement of coal by energy sources with a lower $CO_2$ impact, e.g. natural gas and/or electricity.

Based on the overall performance ($CO_2$, cost and technological) of each of the process routes, the ULCOS steering committee selected the ISARNA concept for further evaluation in the second part of ULCOS. This part is in progress and mainly consists of pilot plant tests for ISARNA to demonstrate the concept. The pilot plant is currently being engineered.

**Table 1.** Results of the $CO_2$ evaluation by ULCOS

| | Reference (BF) | RHF-EAF | FB-EAF | ISARNA |
|---|---|---|---|---|
| **Primary energy** | **100%** | **107%** | **127%** | **83%** |
| **$CO_2$ Base case** | **100%** | **89%** | **96%** | **79%** |
| **$CO_2$ Max Biomass** | **-** | **27%** | **32%** | **7%** |
| **$CO_2$ Max CCS** | **-** | **46%** | **56%** | **20%** |

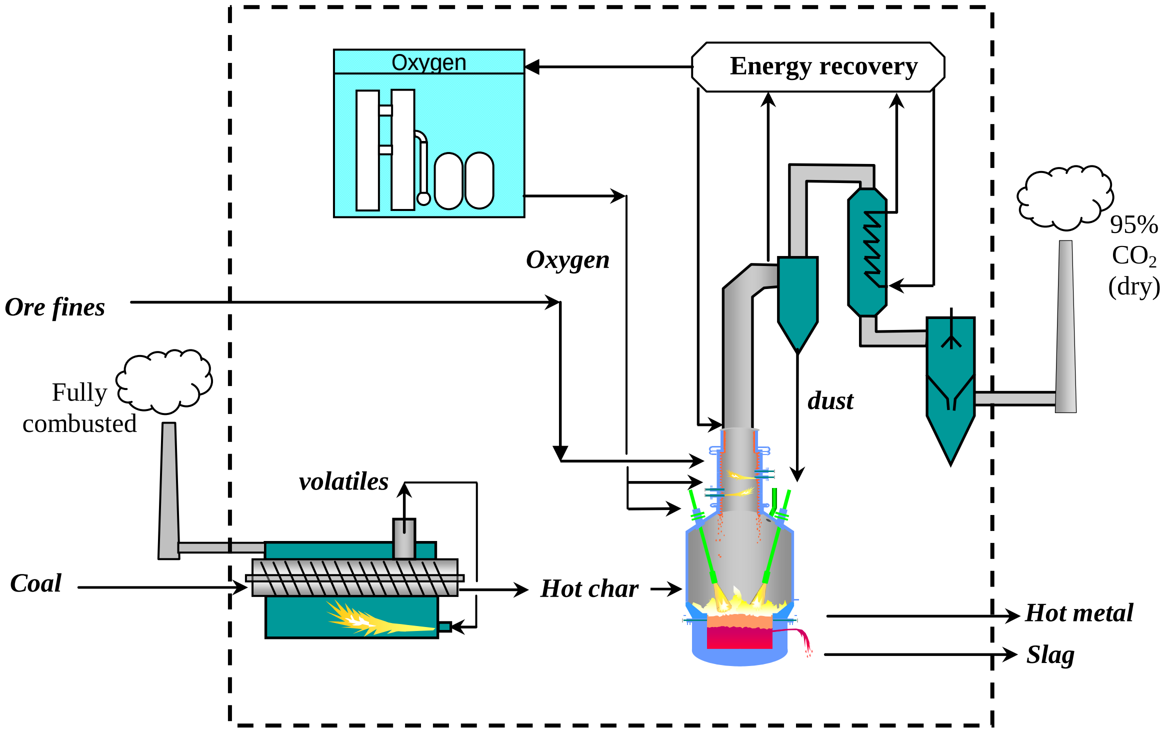


**Figure 1.** Overview of the ISARNA concept

## Case study: ISARNA

### *Process description*

In this section, an overview of the ISARNA process is presented in Figure 1. The core of the process consists of three reactors; a smelting cyclone, a smelting reduction vessel (SRV) and a coal pyrolyser.

Fine ore and flux are fed to the smelting cyclone together with oxygen. The oxygen is used to combust the SRV off gas entering from the bottom of the cyclone. The combustion, which is preferably complete, generates a considerable amount of heat. This heat is used to melt the ore and heat it to the SRV temperature. Simultaneously, the ore is pre-reduced to a pre-reduction degree of about 20% through thermal decomposition and reduction by the SRV gas:

$$Fe_xO_y(s) + CO/H_2(g) = Fe_xO_{y-1}(l) + CO_2/H_2O(g) \quad (1),$$

while the flux is calcined:

$$CaCO_3(s) = CaO(l) + CO_2(g) \quad (2)$$

$$CaMg(CO_3)_2(s) = CaO(l) + MgO(l) + 2CO_2(g) \quad (3)$$

After the molten ore droplets hit the wall of the cyclone, they flow down the wall and drop into the SRV bath. The capture efficiency of the cyclone is maximized by increasing the rotational velocity through the injection of oxygen and ore.

In the SRV bath the remainder of the reduction takes place. The molten droplets of iron ore drop into the bath where they are reduced with carbon from the bath:

$$Fe_2O_3(l) + [C]_{Fe}/C(s) = 2FeO(l) + CO(g) \quad (4)$$

$$FeO(l) + [C]_{Fe}/C(s) = Fe(l) + CO(g) \quad (5)$$

Non-coking coal is supplied to the bath, where it either enters the slag layer or is absorbed in the metal:

$$C(s) = [C]_{Fe} \quad (6)$$

A set of lances, injecting oxygen into the freeboard above the metal bath, combust a large fraction of the gases released within the bath, producing large amounts of energy. Combustion energy is carried back to the bath by the slag and/or metal droplets that are thrown into the freeboard by the gas flow from the bath.

Before the coal is injected into the SRV it can be partially pyrolysed and pre-heated. The combustion value of the volatile components that are released during partial pyrolysis can be used to supply the heat for this partial pyrolysis. By pre-heating and partially pyrolysing the coal, the heat requirement of the SRV is reduced, while the attainable post-combustion ratio in the SRV is increased.

The ISARNA process produces liquid hot metal that can be processed in a basic oxygen furnace or EAF plant.

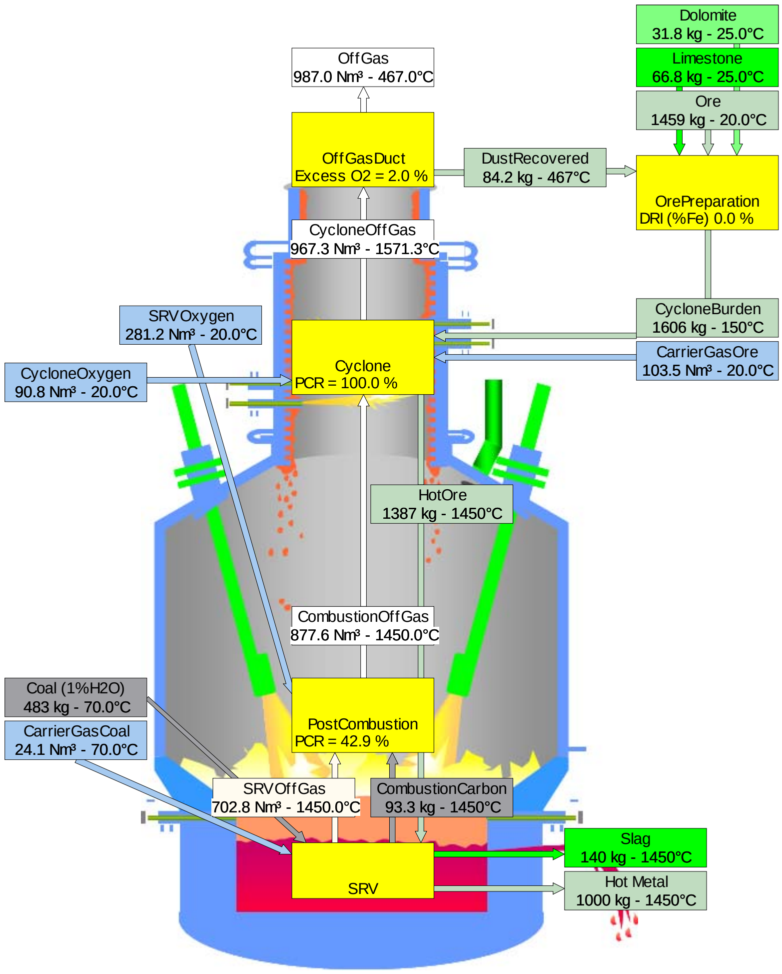


**Figure 2.** IRMA model for the ISARNA concept

## *Process implementation*

Figure 2 shows the ISARNA IRMA model, which is divided into 5 areas that represent the main sections of the process:

- Ore preparation
- Cyclone
- Post-combustion
- SRV
- Off gas treatment

Each section consists of one or more unit operations, depending on the amount of detail that is desired. The division allows the development of different models for each section to represent different process options, e.g. different type of ore or coal preparation.

Apart from the unit operations, the flow and composition of the input streams to the process need to be specified. Subsequently, the streams connecting the sections can be calculated. The calculations use a number of couplings to enforce the specified inlet and product compositions and to align temperatures. Constraints are used to determine the consumption rates of the feed materials.

## *IRMA contribution to ISARNA*

In the first part of ULCOS, IRMA has been used to calculate the consumption figures of the process and to optimize the process.

In the second part of ULCOS, IRMA is being used to design a pilot plant and to evaluate the suitability and required volume of various raw materials that are considered for the pilot plant. It is intended to add process monitoring, control and simulation capability to IRMA to expand its contribution to the project.

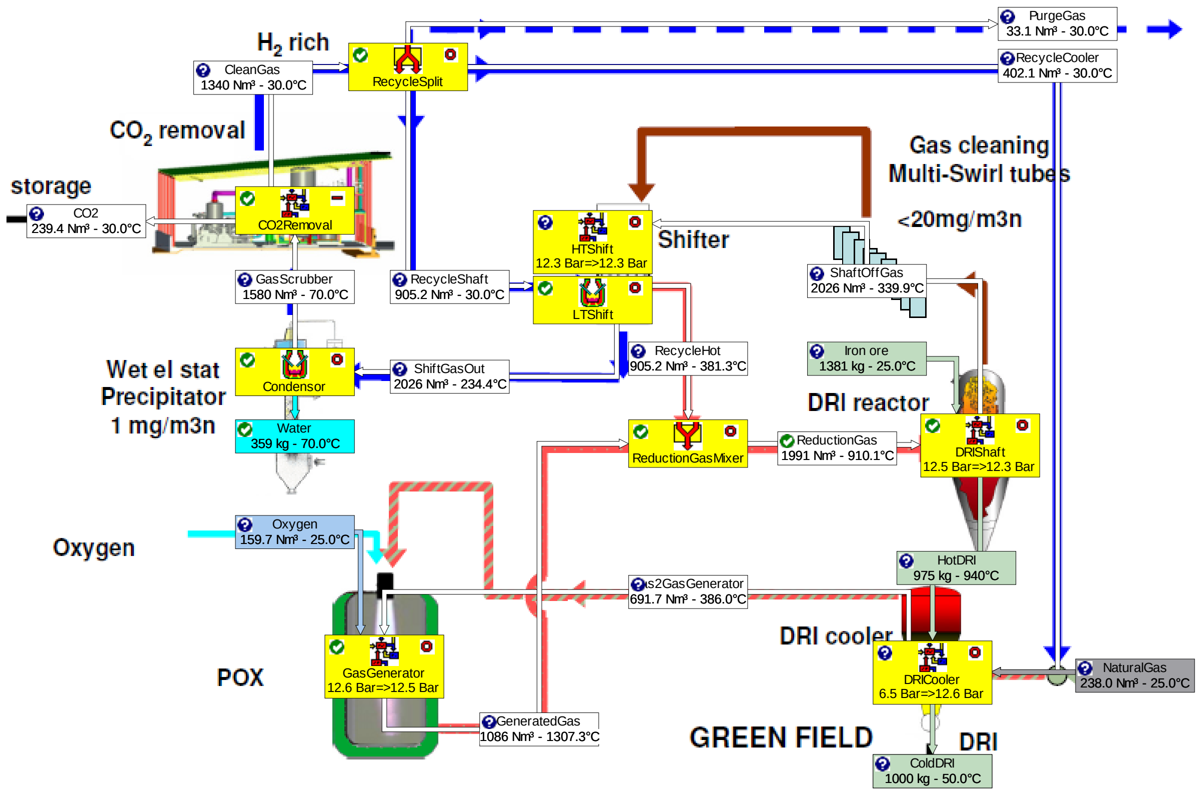


**Figure 3.** IRMA model for the ULCORED concept

## Case study: ULCORED

After IRMA demonstrated its suitability to serve as a selection and evaluation tool within the ULCOS smelting reduction subproject, which is due to its capability to compare processes on the same platform with the same raw materials, the ULCOS direct reduction subproject decided to use IRMA as a review tool for their flowsheeting work.

### *Process description*

ULCORED is the gas based process route developed by the ULCOS direct reduction subproject [7].

### *Process implementation*

Figure 3 shows the ULCORED IRMA model for the case with the lowest natural gas consumption, i.e. the case where a VPSA is employed for $CO_2$-removal and 99.8% pure oxygen is used.

The model is divided into 5 areas that represent the main sections of the process:

- Main reactor, consisting of a DRI shaft and a DRI cooler
- Gas generator
- Shift reactor, consisting of a high temperature shift, a low temperature shift and a heat recovery unit
- Gas cleaner, consisting of a condenser and a $CO_2$-removal
- Afterburner

The flowsheet design follows the design made by the ULCOS direct reduction subproject.

Each section consists of one or more unit operations, depending on the amount of detail that is desired. The division allows for the development of different models for each section to represent different process options, e.g. different types of $CO_2$-removal.

Apart from the unit operations, the flow and composition of the input streams to the process need to be specified. Subsequently, the streams connecting the sections can be calculated. The calculations use a number of couplings to enforce the specified inlet and product compositions and to align temperatures. Conditions are used to determine the consumption rates of the feed materials. The minimum natural gas rate was determined by trial and error.

### *IRMA contribution to ULCORED*

Currently the IRMA model is used for reviewing the flowsheeting model used in SP12. In the future, IRMA models of MIDREX and HYL will be made, which will serve as benchmarks for the ULCORED process.

## Conclusions

To support the process route evaluation within the ULCOS smelting reduction subproject, a modelling platform for the comparison of a wide variety of ironmaking routes has been developed in the form of the flowsheeting tool, IRMA. This modelling tool has been successfully validated and the tool has been used to develop models for a wide variety of ironmaking process routes. The consumption figures resulting from these steady-state calculations were in good agreement with models used by the ULCOS partners.

The consumption figures calculated using IRMA have made a considerable contribution to the ULCOS selection process. The outcome of the selection process is that the development of ISARNA is being continued within ULCOS. IRMA continues to play an important role in the development of ISARNA and is now also used for the development of ULCORED within ULCOS.

## Future development

Improving the user-friendliness of the modelling tool is a continuous effort in the development of IRMA. It is envisioned that by adding dynamic capability to IRMA its ability to contribute to process control, monitoring and simulation can be increased.

## Acknowledgements

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## References

[1] R. Dry and N. Goodman: "HIsmelt plant ramp-up", Scanmet III conference proceedings, 2008, Volume I, 173-181.

[2] K. Badr: "Smelting of Iron Oxides Using Hydrogen Based Plasmas" (Ph.D. thesis, Montanuniversität Leoben, 2007).

[3] Th. Hansmann, P. Fontana, A. Chiappero, I. Both, and J.L. Roth: " Technologies for the optimum recycling of steelmaking residues", Stahl und Eisen, Volume 128-5/2008, 29-35.

[4] K. Förster, A. Orth and J.-P. Nepper: "Direct reduction of iron ore based on Circofer and its product versatility", Volume I, 213-221.

[5] C. Bartels-von Varnbüler, M. Lemperle and H.J. Rachner, "Recovery of iron from residues using the Oxicup technology", MPT international, Volume 1/2006, 18-26.

[6] H.K.A. Meijer, J. van Laar, W. van der Knoop and R. van Nederveen: "The engineering of a cyclone converter furnace (CCF) plant", Proceedings of the 3rd European Ironmaking Congress, 1996, 321-325.

[7] K. Knop, E. Burström: "The New DR process", this seminar.

## Abbreviations

| | |
|---|---|
| BF | Blast furnace |
| DRI | Direct reduced iron |
| EAF | Electric arc furnace |
| FB | Fluidized bed |
| Max | Maximum |
| RHF | Rotary hearth furnace |
| SP | Sub-project |
| SRV | Smelting reduction vessel |
| VPSA | Vacuum pressure swing adsorption |

[1] Priority 3 of the 6th Framework Programme in the area of "Very low $CO_2$ Steel Processes", in co-ordination with the 2003 and 2004 calls of the Research Fund for Coal and Steel