Development of an Operator Guidance System for Intermediate Carbon Charge Chromium Production

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ABSTRACT

Development of an Operator Guidance System (OGS) to control a 30 t Creusot-Loire-Uddeholm (CLU) converter, located on the Ferrometals Plant of Samancor, for production of Intermediate Carbon Charge Chromium (IC3) is described. The process involves bottom injection of oxygen and steam, to effect decarburisation (De-C) of feed charge chromium (ChCr) containing greater than 6% C to produce IC3 of between 1-4% C content.

The OGS is based upon a phenomenological heat and kinetic mass transfer model, which takes into account the transitory gas bubble/slag/metal and permanent contact top slag/metal reactions. The capability of the model to predict key converter performance parameters (C content, temperature and Cr recovery to alloy) is demonstrated through comparison with actual plant operating data. Application of the OGS to dynamically recommend suitable gas injection rates and coolant additions to effect control of the commercial converter operation is presented.

INTRODUCTION

IC3 containing 1-4% C has been produced commercially since 1986 and involves the staged batch oxygen refining of liquid ChCr analysing 5-8% C, <6% Si and 50-55 % Cr in a 30 t CLU converter (Figure 1). Despite substantial improvements made to the production of IC3 in the CLU converter at Ferrometals over the past decade[1,2,3], the need was identified for even tighter metallurgical process control to further:

- increase productivity and effective plant capacity
- lower cost of production through enhanced process efficiency
- improve product quality
- increase the range of marketable product grades.

To effect such improvements, an OGS has been developed to control the CLU converter. The most critical stage, from a control perspective, is the De-C stage which yields the final IC3 product. The OGS has primarily been focused on this De-C stage. The OGS has the capability of predicting the likely performance of the batch process through some future time, based on prevailing process conditions. Once accepted in the plant environment, the OGS will ultimately be upgraded to deliver dynamic control over the CLU converter process.

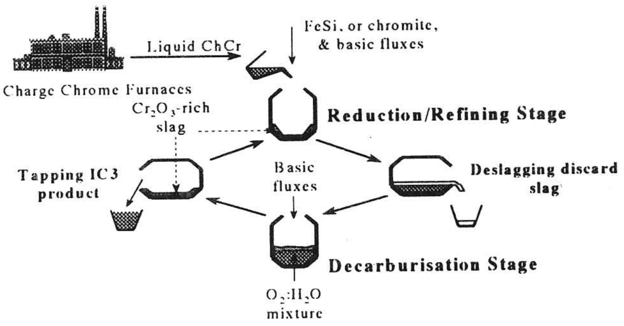

Figure 1: Schematic of overall IC3 production process in a CLU converter

The CLU converter at Ferrometals is bottom blown with a mixture of oxygen and steam to effect De-C (Figure 2). The steam dissociates in contact with the melt to form hydrogen and oxygen. The hydrogen acts as a diluent gas and lowers the partial pressure of the CO that forms in the De-C reaction, thereby fulfilling the same role as argon in the Argon Oxygen Decarburisation (AOD) process. In addition, the endothermic dissociation of the steam can be used to control temperature in the exothermic refining process, so limiting converter refractory lining attack.

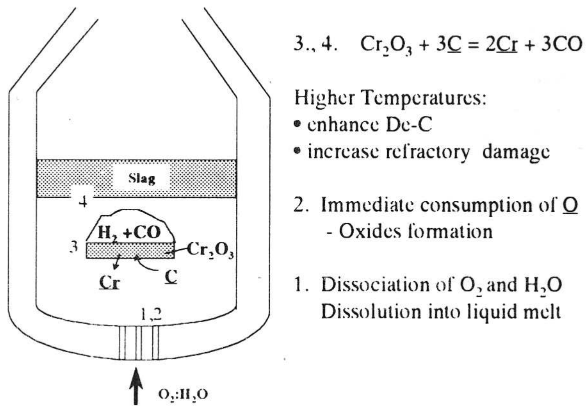

Figure 2: Schematic representation of the CLU converter De-C process

De-C Reactions of ChCr

The two main sites at which refining reactions occur in the converter are:

1. Transitory reaction site
2. Permanent contact reaction site.

Transitory reaction site

Transitory reactions refer to the reactions between the gas bubbles and the metal as the injected gases rise through the melt. As soon as the injected oxygen contacts the metal at the tuyere tip, it dissolves in the metal and reacts near instantaneously with elements dissolved in the metal bath. Due to a high local oxygen potential, the different elements that can be oxidised react in amounts roughly proportional to the atomic percentage of each element present in the melt. If only the dissolved C and Cr are considered, the following reactions occur at the tuyere tip:

$$\underline{C} + \underline{O} = CO\,(g) \qquad (1)$$

$$\underline{Cr} + x\underline{O} = CrO_x\,(s,l)$$

where: $x = 1, 1^1/_3, 1½$ (2)

For simplicity of illustration, x is chosen to be 1½, so CrO_x represents Cr_2O_3. As the slag-laden bubble rises through the metal, the Cr_2O_3 contained reacts with the C in the metal according to:

$$Cr_2O_3\,(s) + 3C = 2Cr + 3CO(g) \qquad (3)$$

$$\ln K = \ln\{a_{Cr}^2\ p_{CO}^{\ 3} / a_{Cr_2O_3}\ a_C^{\ 3}\}$$
$$= -84650/T + 54.63 \qquad (4)$$

where:
K = equilibrium constant
T = temperature, K
a_{Cr} = activity of Cr
p_{CO} = partial pressure of CO, atm
$a_{Cr_2O_3}$ = activity of chromium oxide
a_C = activity of C

From Equation (4) it can be seen that C oxidation according to Reaction (3) is favoured by a low a_{Cr} and a high a_C in the metal, a high $a_{Cr_2O_3}$ activity, and a low p_{CO} in the gas phase. From the expression it is also clear that the extent of C oxidation is enhanced by a high temperature, but an upper limit is imposed on it by the need to ensure an acceptable extent of refractory wear.

For reasons of computational efficiency, the transitory slag is assumed to be Cr_2O_3-saturated (i.e., $a_{Cr_2O_3}$ assumed to be unity) in the OGS. Representation of the slag in this simplified manner has not been found to introduce significant effect on OGS predictions.

Permanent contact reaction site

Permanent contact reactions refer to the reactions occurring between the metal and the overlying top slag. The De-C reaction at this site is essentially due to Reaction (3). In the normal De-C stage of the converter, the slag is more or less solid (referred to on the plant as a "dry" slag), consisting of a molten slag phase saturated with chromium oxide and a solid chromium oxide-bearing phase.

REACTION KINETICS

The specific rate controlling step in De-C is one of the following[4,5]:

1. the flow of oxygen into the bath
2. the equilibrium given by Reaction (3)
3. mass-transfer of C from the bulk metal phase to the interface

A typical De-C profile reported on the plant for IC3 production[2] exhibits this classical kinetic behaviour (Figure 3). The chemical reactions taking place at the phase interfaces, at the high temperatures and relatively low pressures characteristic of pyrometallurgical processes, are fast and so are not normally rate-controlling.

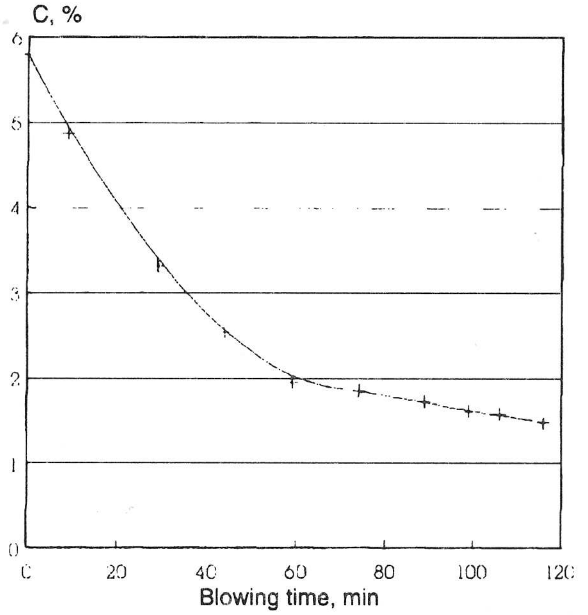

Figure 3: A typical De-C profile with time

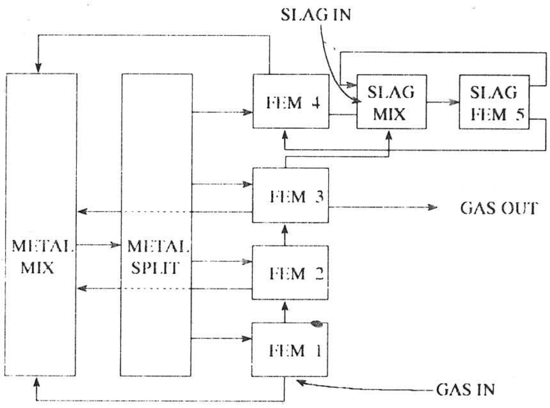

Figure 4: OGS representation in METSIM

DESCRIPTION OF MATHEMATICAL MODEL

The METSIM simulation software[6] has been used in the construction of the multi-component, mass-transport based kinetic model. A schematic of the METSIM 'CLU' model is shown (Figure 4). Fundamentals behind this modelling approach have been discussed elsewhere[7,8]. Local chemical equilibrium has been assumed to exist at each of the metal/slag/gas interfaces.

The metal has been conceptually divided into three transitory height steps. The Free Energy Minimiser (FEM) unit operations 1, 2 and 3 represent the transitory reaction of the metal with the gas at the three height steps. The FEM is based on the Solgasmix algorithm[9] and computes the chemical equilibrium state arising from the input elements under the prevailing conditions of temperature and pressure (mid-height step condition has been assumed for the transitory reaction). The FEM unit operation 4 represents the permanent contact reaction between the metal and the top liquid slag. The FEM unit operation 5 represents the reaction between the top liquid and solid slag.

Metal and slag phases have 'mass transfer' streams of bulk composition and mass flowrates kAρ leaving them and entering the respective FEMs. Since the k of the gas is very high compared to that of the metal, it is assumed that all the injected gas substantially attains equilibrium with the mass transfer flow of the metal at each height step. The input streams to the FEM are brought into equilibrium and then are split into phases, including any newly formed phases, such as solid or gas. The slag and metal phases from the FEM are returned to the bulk so that the net rate of transfer for every species into the phase (W, in units of kg/min) is given by the expression:

$$W = k'A'\rho'w_s - kA\rho w_b \qquad (6)$$

where ρ, ρ' = total mass concentration (density) of the phase, kg/m^3
w_s = mass fraction of a species at the surface, at equilibrium
w_b = mass fraction of a species in the bulk
k, k' = mass transfer coefficient, m/min
A, A' = surface area between the phases, m^2
= refers to the values in the stream coming out of the FEM.

This expression therefore directly includes the effects of bulk flow on the mass transfer rate and exactly describes the condition of mass transfer control.

A user-friendly interface has been developed. The interface allows the operator to change the compositions and temperature of metal and slag, and the gas injection rates. The graphical output screen shows the dynamic change in the C content, temperature of metal, Carbon Removal Efficiency (CRE)[*], and rate of C removal from the metal (dC/dt)[+]. The CRE and dC/dt are particularly important to distinguish to permit the plant to operate optimally under prevailing market conditions of reduced and high IC3 alloy demand, respectively. Additionally, the CRE is interpreted to be an effective instantaneous measure of Cr recovery to the alloy—important in view of the strong influence of delivered ChCr on the overall cost of IC3 production. The operator can decide on corrective action to maintain the CRE and/or the dC/dt at the highest levels possible based on the predictions of the model, while still ensuring that the desired alloy end point is achieved.

Thermodynamic Data and Solution Models

Thermodynamic data from standard sources have been used for all the components in the model. An Interaction Parameter approach (involving $Fe_{solvent}$–Cr–C–Si) has been used to calculate the activity of species in the metal. A Regular Solution model approach has been used to calculate the activity of species in the liquid slag (involving Cr_2O_3–CrO–FeO–Al_2O_3–MgO–CaO–SiO_2).

Heat Loss Data

A heat balance trial was performed on the converter. Near the end of a heat, when the temperature of the metal was around 1660°C, the metal was allowed to stand for a period of 40 minutes with injection of nitrogen through the bottom tuyeres at a rate of 19 Nm^3/min. The temperature of the outer shell of the converter was measured using weld-patch thermocouples during the trial period. Measurements of the temperature of the metal were taken every 5 minutes using quick immersion thermocouples. Metal samples were also taken during this time. The temperature was used to calculate a constant heat loss term of 0.36 °C/min for the converter for a given state of refractory wear. This corresponds favourably with reported values of 1-3 °C/min on 45 to 100 t AODs[5,10,11,12]

Model Parameters

Permanent contact mass-transfer rates

The metal chemical analysis data of the heat balance trial were used to calculate the permanent contact mass-transfer rate of metal. Since nitrogen was injected during the trial, all the C removed from the metal during the trial must have been through the permanent contact reaction between the metal and the top slag, discounting any net reaction of the C with dissolved oxygen in the metal. This gave a permanent contact metal mass-transfer flow of 110 kg/min. On the assumption that the mass transfer coefficient of slag is roughly half that of the metal and that the density of slag is 3.5 x 10^3 kg/m^3, the top slag mass transfer flow was estimated to be 29 kg/min.

Transitory reaction mass-transfer rates

The precise value for the metal/gas interfacial area is not known since it is highly dependent upon the size distribution and shapes of the gas bubbles in the melt. Literature data[8,12,13,14] on the metal mass transfer coefficient also vary between 1-10 x 10^{-4} m/s. Because of these uncertainties, the transitory metal mass transfer rate has been treated as an adjustable "lumped" parameter (kAρ). A value of 2.1 x 10^{-3} kg/min has been found

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[*] CRE = the efficiency of utilization of oxygen in effecting De-C – a good measure of process efficiency.

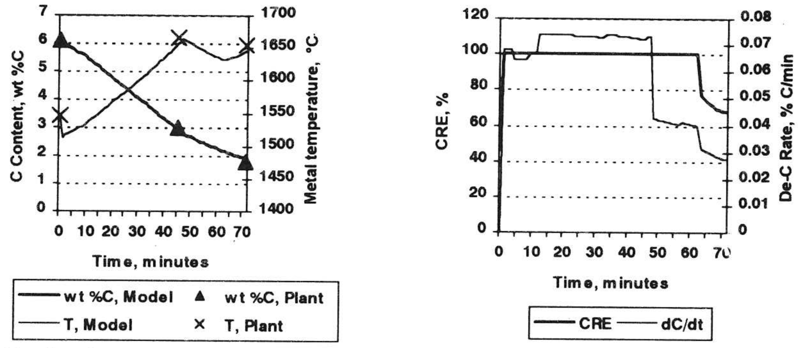
[+] dC/dt = the instantaneous rate of change of C content in the alloy – a good measure of productivity.

Table 1: Heat A data (no coolant scrap addition)

Nominal Blow Ratio Nm³/min	Blow Time min	C Content wt %C	C Content wt %C	T_{metal} °C	T_{metal} °C
		Plant	Model	Plant	Model
Initial		6.1		1547	
22/7	4				
22/7	3				
22/7	3				
22/7	34	3.0	2.94	1667	1656
22/7	2				
7/13	24	1.8	1.91	1656	1645
30740 kg	Metal tapped				

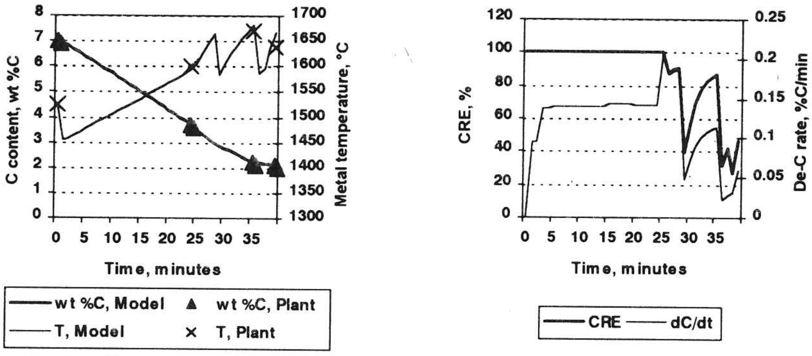
Table 2: Heat B data (with coolant scrap addition)

Nominal Blow ratio Nm³/min	Blow Time min	C Content wt %C	C Content wt %C	T_{metal} °C	T_{metal} °C	Scrap kg
		Plant	Model	Plant	Model	
Initial		7.0		1524		
12/7	2					
22/7	4					
22/7	18	3.7	3.71	1602	1594	
22/7	4					
22/7	7	2.2	2.25	1670	1681	950
8/7	2					950
22/7	2	2.1	2.09	1639	1667	
16780 kg	Metal tapped					



(a) alloy C content and temperature (b) % CRE and dC/dt

Figure 5: Heat A predicted versus actual results (no coolant scrap addition)



(a) alloy C content and temperature (b) % CRE and dC/dt

Figure 6: Heat B predicted versus actual results (coolant scrap additions)

to best fit the data from several heats. This is equivalent to a kA/V of 0.07 min^{-1} for a typical 30 t heat and compares well with a value of around 0.1 min^{-1} used in prior AOD simulations[4,5,10,11,12,13,14].

OGS PREDICTIONS

The results of the kinetic model simulations for two typical heats and the actual heat data are shown (Tables 1 and 2 and Figures 5 and 6). The correspondence between actual plant and calculated model results is good.

Initially, once the alloy Si content is substantially consumed by oxidation, and when the C content of the metal is high, the activity of Cr is suppressed and all the oxygen supplied is consumed by C. This results in a CRE of 100%. At this point, the reaction is controlled by oxygen supply. Below a critical C content[15] (primarily dependent on oxygen:steam ratio, temperature and Cr/Fe of the metal, and slag a_{CrO_x}) the CRE starts decreasing, through highly exothermic oxidation of Cr at the expense of C. This is accompanied by a decrease in dC/dt. At this stage, the reaction is chiefly controlled by liquid metal mass transfer of C.

Effects of Transitory Height Steps in Model

The effect of the number of height steps chosen to represent the transitory reaction on the final metal C content and temperature is illustrated (Figure 7). It is seen that there is a marked difference in the alloy C content and temperature predicted from a one to a two height step case. Increasing the height steps from three to four changes the predicted C content by only 0.007%C and the predicted temperature of metal by 0.41°C over the full duration of a blow of 39 min. In view of the increased computational overhead of using several height steps, without significantly increasing the accuracy of the calculations, all simulations presented are for the condition of three height steps.

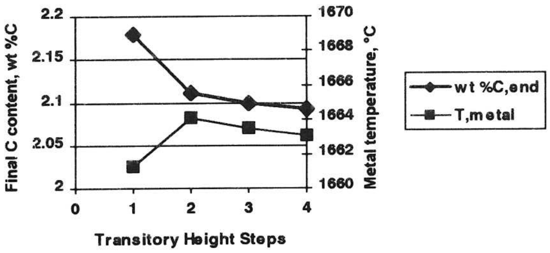


Figure 7: Variation of the predicted metal C content and temperature with number of transitory height steps

SENSITIVITY ANALYSIS

Sensitivity analyses were performed to determine the effects of key variables on the critical measured output variables, metal C content and temperature (Figures 8 and 9). The sensitivities of input process and model variables are shown. In the actual plant analysis, the process capability was additionally superimposed on the abscissa to permit the relative importance of the variables to be ranked. This allowed attention to be focused on the sequence of items to be tackled for de-bottlenecking the plant.

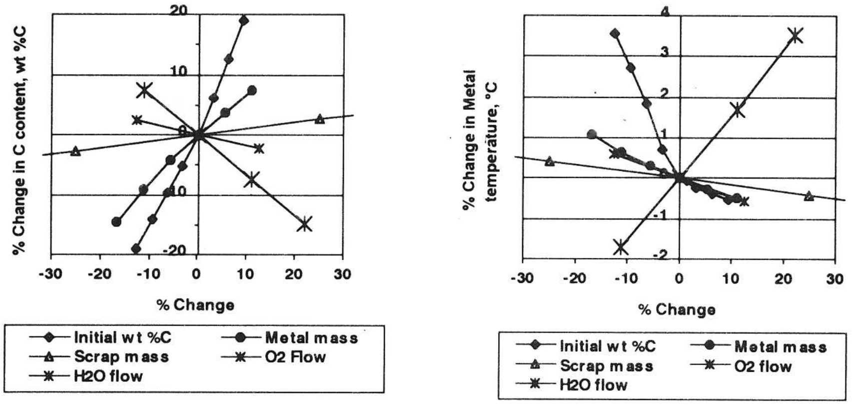
Key Process Variables

Effects of gas flowrates

A 1% increase in the oxygen gas flowrate lowers the final C content by 0.5% (from 2.10 to 2.09 %C) and increases the final metal temperature by 0.15% (from 1592.7 to 1595.1 °C). As would be expected from the fact that O_2 dissociates to $2\underline{O}$, while H_2O dissociates to $\underline{O}$ (and H_2), the effect of oxygen gas flowrate on the final metal C content is twice that of steam. The final metal temperature is raised by increasing the oxygen flowrate (exothermic refining reactions are promoted), while the effect of the steam flowrate is the inverse (the reaction of steam, including dissociation, is net endothermic).

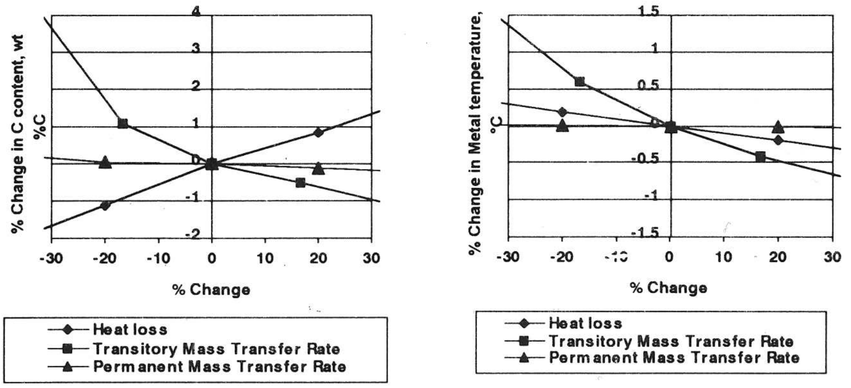
Effects of initial C content

A 1% error in the initial metal C content produces a predicted 2% error in the final C content and a predicted 0.28% error in the final temperature of metal. This emphasises the need for accurate measurement of initial ChCr C content on the plant.



(a) Effect on final metal carbon content (b) Effect on final metal temperature

Figure 8: Sensitivity analysis of process variables on process outputs



(a) Effect on final carbon content (b) Effect on final metal temperature

Figure 9: Sensitivity analysis of some model variables on process outputs

Effects of coolant scrap addition

The effect of coolant scrap addition is dramatic if it causes the metal temperature to drop so low that it creates a condition where the metal C content falls below the critical C at which Cr oxidation over De-C becomes favourable. Notice how the CRE drops when excessive scrap additions are made (Figure 6b). However, smaller scrap additions only have a marginal effect on the process (Figure 8).

Effects of Model Parameters

The OGS model predictions on final metal C content and temperature are shown to be relatively insensitive to the three adjustable parameters of the model; namely, heat loss rate, permanent contact and transitory mass transfer parameters (Figure 9). Changes in the two former parameters in excess of 30% yield of the order of an 1% change in the predicted final alloy state in terms of C content and temperature. Changes in the transitory mass transfer parameter have slightly more marked effects – 30% change yields a maximum 4% change in the final C content (from 1.94 to 1.86 %C).

PLANT IMPLICATIONS OF OGS

Evaluation of the OGS predictions of just two actual plant De-C heats shows that there is considerable scope for improving the efficiency and consistency in the blowing cycle, particularly in terms of improved CRE and higher dC/dt. Specifically, an OGS should help to better, or at least emulate, the performance of the "best plant operator". This will accrue plant benefits due to shorter heats and less frequent overblowing of heats to achieve the desired C and temperature endpoints, directly leading to operating cost savings in terms of:

- reduced losses of expensive Cr units to oxidation;
- diminished converter refractory lining wear;
- decreased reactive gas consumption;
- lowered reductant (expensive ferrosilicon) and basic flux consumptions, and higher Cr recoveries in the subsequent reduction/refining stage.

Blowing Sequence and Control

The CRE and dC/dt can be maintained at a high level throughout the blow by changing the total gas flowrate and the oxygen:steam ratio of the gas. The changes can be effected stepwise (i.e., blow at a set rate until a predetermined condition has been attained) or in a continuous fashion (to maintain the CRE and dC/dt at the optimum critical C set-point value permanently, as proposed by Szekely, et al.[15]).

Recommendation of the optimum gas flowrates and scrap coolant additions in a stepwise approach is the goal of the initial on-line OGS. Later, it is hoped that a continuous blowing rate optimisation algorithm will be incorporated into a full control model, to optimise the CRE and dC/dt for the entire period of the blow based on the initial conditions of the heat.

Top Lance

The OGS predictions suggest that during the initial period of the blow dC/dt can be increased significantly, without compromising the CRE, by increasing the oxygen injection rate. This can be done to an extent by upgrading the existing bottom gas delivery system at the plant. Installation of a top injection lance is another option. The OGS can be readily modified to accommodate this latter condition, either by conceptually:

- "releasing" the injected gas at a predetermined bath depth as a function of top injection rate[16]
- increasing the mass transfer rates as functions of top gas injection rate[17].

An additional benefit perceived for operation with a top lance in ChCr refining, is that a localised hot spot will develop—thermodynamically and kinetically favouring De-C relative to Cr oxidation.

Upgrade of Plant Instrumentation

Sufficient and accurate instrumentation is a prerequisite for reliable OGS performance. A detailed evaluation of the capability of the process identified a significant deficiency regarding measurement of the Si content of the incoming ChCr. To address this shortcoming, a rapid solid-state Si sensor system was developed for on-line determination of the input ChCr Si content[18].

Other Less Tangible Benefits

A number of other benefits can be attributed to the joint OGS development program on the plant, but these are difficult to quantify. Yet, distinct benefits have already been realised through the OGS development program due to the enhanced level of process understanding generated.

Specifically, a statistically significant improvement of 76.6% in the mean converter refractory lining life was achieved, from a mean of 78.7 heats in the period prior to the OGS project (but excluding the period of the first 28 campaigns when fettling was not practised[2]), to a mean of 139 heats since its inception in 1995 (Figure 10). This improvement can primarily be traced to selection of better refractories for the converter lining and a proactive plant fluxing practice, but both developments were instigated following auditing of plant practice for the OGS.

CONCLUSIONS

An off-line OGS has been successfully developed to simulate production of IC3 on a 30 t CLU converter. The OGS has been shown to be capable of predicting plant De-C data very accurately. Sensitivity analysis of the process and model variables on the final alloy C content and temperature has helped in identifying important process and model variables. The OGS can also compute the CRE and dC/dt, so guiding the operator on selection of the optimum blowing schedules. On-line implementation of the OGS to dynamically recommend (and ultimately control) the IC3 production process has commenced, with final delivery of the system scheduled for mid-1998.

ACKNOWLEDGEMENT

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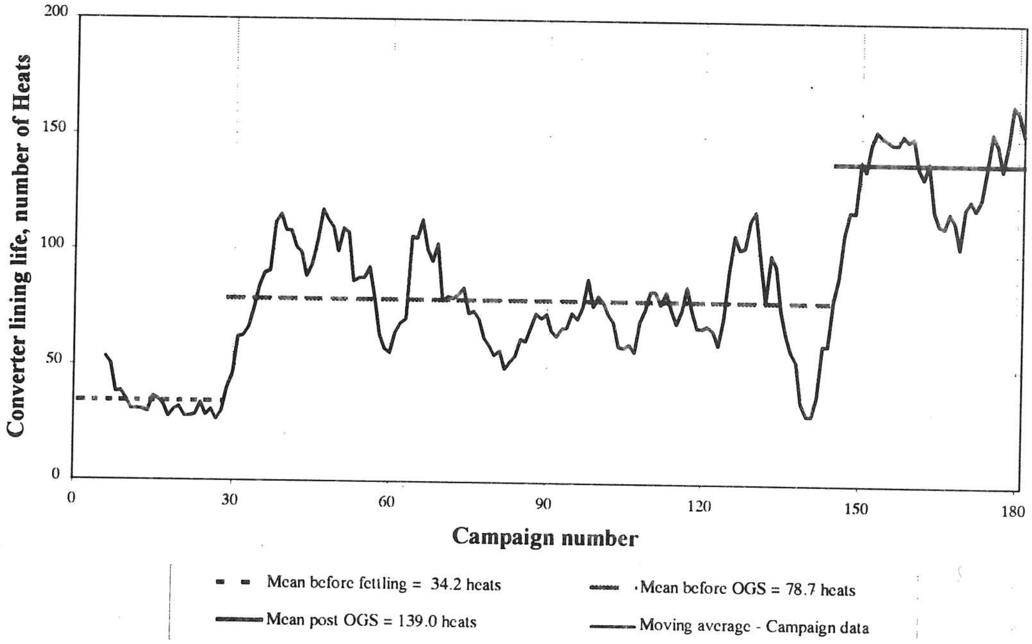

Figure 10: Chronological sequence of improvements in converter lining life

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