APPLICATION OF A HIGH-INTENSITY COOLING SYSTEM TO DC-ARC FURNACE PRODUCTION OF FERROCOBALT AT CHAMBISHI

L.R. Nelson, R. Sullivan[1], P. Jacobs, E. Munnik, P. Lewarne, E. Roos[2], M.J.N. Uys[3], B. Salt[4], M. de Vries, K. McKenna, N. Voermann[5] and B.O. Wasmund

[1] HATCH, Woodmead, South Africa; lnelson@hatch.co.za
[2] Chambishi Metals plc, Kitwe, Zambia; edwinr@chambishi.com.zm
[3] Anglovaal Mining Ltd., Johannesburg, South Africa; Thysu@avmin.co.za
[4] Falconbridge, Sudbury, Canada; bsalt@sudbury.falconbridge.com
[5] HATCH, Mississauga, Canada; nvoermann@hatch.ca

ABSTRACT

A review is presented of the furnace cooling system design and operating developments since the initial furnace start up in January 2001 of the Chambishi DC-arc furnace to produce ferrocobalt alloy. The furnace operating conditions present a number of challenges to the furnace designers and operators in particular to provide a sustainable lining that can withstand the highly corrosive siliceous slag (roughly 50% SiO_2). This is exacerbated by the dual requirement to operate this slag in a relatively highly superheated state ($\Delta T \approx 400°C$ when tapped at 1550°C) to ensure that the ferroalloy can be tapped (estimated 1370°C alloy liquidus temperature) prior to atomisation.

The core design challenge occurs at the alloy-slag interface, where a single refractory type cannot simultaneously meet the dual requirement of both adequate alloy and slag corrosion compatibility. Progression by the fourth furnace campaign to involve a retrofit of the bath sidewall to Hatch high-intensity, water-cooled, copper Waffle coolers and tapblocks is described. This involves operation of the entire slag bath, the slag-alloy interface and a portion of the alloy within a more chemically compatible refractory/slag (and possibly at times even an alloy) freeze-lining. Due to the high furnace power density employed (up to 500 kW/m^2 hearth area) coupled with the large slag superheat needed, the resulting imposed peak bath sidewall heat fluxes are substantial, especially in the alloy (typically averaging 170 kW/m^2), and on occasion have exceeded 1000 kW/m^2.

The performance of the Hatch Copper Waffle coolers under such aggressive process pyrometallurgical conditions is described. Aspects of the design and especially operating strategies to effect sustained production at up to 38 MW power input are also discussed.

1 INTRODUCTION

The production process is somewhat unique, involving selective carbothermic reduction of crushed (to -22mm) cobalt- and copper-containing revert slag to produce a copper-containing ferrocobalt alloy (typically of 14% Co and 14% Cu contents) [1]. The alloy is atomised following tapping and subsequently leached by sulphuric acid under high-pressure and oxidative conditions in autoclaves [2] to yield cobalt liquor that is purified via precipitation and ion exchange processes [3], and subsequently recovered by conventional electrowinning.

The original design of the furnace bath sidewalls was found incapable of withstanding the operating conditions and following rapid loss of refractory linings resulted in a runout after furnace commissioning and again, following some minor refractory improvements, some few months later. This culminated in August 2002 in the furnace sidewalls being rebuilt, with the existing copper coolers being replaced with Hatch water-cooled copper Waffle coolers and tapblocks (Figures 1, 2 and 3). Shell plate modifications were also made to incorporate the Hatch spring-loaded hold-down system (Figure 2) that provides a vertical compressive force between these coolers and the hearth skew bricks to ensure tight joints between bricks and cooling elements, thereby minimizing the potential for penetration of metal or slag in these joints [4,5,6]. The shell plate changes also accommodate external replacement of coolers and tapblocks.

Proceedings: Tenth International Ferroalloys Congress;
INFACON X: '*Transformation through Technology*'
ISBN: 0-9584663-5-1

1 – 4 February 2004
Cape Town, South Africa
Produced by: Document Transformation Technologies

It was recognized that the refractory loss on the sidewalls due to chemical and thermal attack by the slag, could not be resolved by alternative material selections. The Hatch Waffle coolers were selected for their ability to form and retain slag freeze coatings that provide an effective sidewall lining that can withstand the slag and metal and high resultant heat fluxes encountered. The current Campaign #4 covers the operation with the new bath sidewall design.

Figure 1. View inside furnace during installation of the Hatch Waffle coolers

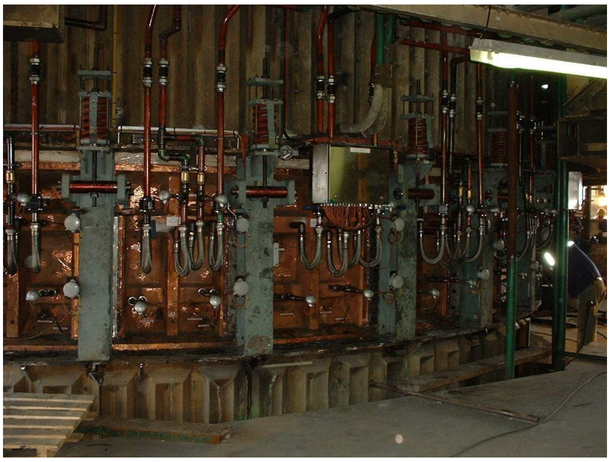


Figure 2. View of spring hold-down system and Waffle coolers

Figure 3. Exterior view of matte taphole side of the furnace

Figure 4. Furnace tapping matte following Waffle cooler retrofit

2 KEY FURNACE ELECTRICAL

At 40 MW operation, the key characteristics of the DC electrical supply are:

- Electrode voltage = 500 - 1200 V DC
- Electrode current = 33 - 60 kA (60kA is a practical transformer limit)
- Resistance = 12 - 35 mΩ (typical operating range).

3 INITIAL FURNACE EQUIPMENT (JANUARY 2001)

Bateman-Titaco designed and erected the original furnace comprising:

- 11.0 m water cooled furnace shell
- 9.8 m inside refractory diameter
- 610 mm diameter Fuchs electrode column
- Concast electrically conductive bottom anode and bus system.
- Fuchs bath sidewall coolers and tapblocks. Sidewall cooling consists of 2 rows of smooth face water-cooled copper blocks with a total height of 1.5 m. The blocks extend 100 mm below the metal taphole

and approximately 300 mm above the maximum slag level. The coolers were typically 750 mm high x 540 mm wide for a total of 120 coolers.

- Refractory lining
  - Freeboard – magnesia-alumina spinel brick
  - Slag zone – silicon carbide with carbon ramming mix on the hot face
  - Metal zone – magnesia brick
  - Electrically conductive hearth and anode – magnesia-graphite

4 CAMPAIGN #1

Campaign #1 (24 January – 8 May 2001) terminated prematurely due to brick hydration around a metal tap hole. The bricks were replaced and production restarted.

5 CAMPAIGN #2

Operation at power levels of 25-30 MW was accomplished between 25 July 2001 and 17 January 2002. Initial furnace operations resulted in very rapid refractory loss in the slag and metal taphole zones and a refractory tear-out and furnace reline was carried out. In the last month of operation the furnace was simply used to melt alloy reverts.

6 CAMPAIGN #3

Operations from 15 February to 4 July 2002 were carried out at power levels typically in the range of 20 to 33 MW. The Campaign ended prematurely when there was a runout through the coolers near the south slag taphole.

6.1 Design Changes for Campaign #3

- Magnesia refractory extended higher up the sidewalls above the metal taphole to just below the maximum metal level.
- Graphite tiles were added between the silicon carbide bricks and copper coolers in the slag/metal wash zone.
- Some minor hearth design changes were made.
- Feed ports were added closer to the electrode. The original ports in the water-cooled roof panel were retained.

6.2 Furnace Lining and Operation

The silicon carbide sidewall bricks in the slag zone were substantially washed away within 3 weeks of the operation at 10 MW. Slag chemistry was then modified to create a viscous slag in an effort to create a freeze lining on the bath sidewall. Lime fluxing was stopped, reduction of slag FeO was increased, and magnesia-alumina spinel bricks were added. Temporarily this was effective in bringing down the heat flux on the copper panels, however the freeze lining did not last.

Rutile additions of 5-10% by mass were then made in an attempt to re-establish the freeze lining by tapping slag down to coat the bath sidewalls. This procedure was more effective in reducing bath sidewall heat flux, and resulted in lower slag cobalt losses, but at the expense of an alloy containing lower contents of cobalt and copper and which had higher liquidus temperature and was difficult to atomise.

During this campaign the furnace operated intermittently at typically around 20 to 25 MW and up to a maximum of about 30 MW. The main obstacle to achieving the design power of 40 MW was the inability of the coolers to maintain either refractory or a freeze layer on their hot faces.

The loss of refractories from the cooler hot face due to the corrosive action of the slag also resulted in a reduction in the support of the freeboard lining. Significant areas of freeboard brick then collapsed into the bath forcing the operators to maintain a relatively short arc to minimize the freeboard heat flux.

7 CAMPAIGN #4

Meetings were held in November 2001, between Chambishi and Hatch to review the furnace operation and investigate ways to make the furnace thermally more robust and address the slag/refractory corrosion problems. The following improvements were proposed:

- Install Hatch Waffle type copper bath sidewall coolers and tap blocks.
- Install the Hatch spring-loaded sidewall hold-down system to ensure tight sidewall/hearth joints
- Change refractory materials as follows:
  - Slag zone – alumina-chrome ram mix
  - Metal zone – alumina-chrome in skew area and magnesia in the hearth.

8 DESIGN HEAT FLUXES

The design heat fluxes for the Waffle coolers were based on cooling water temperatures measurements taken during Campaign #2. Although the metal and slag zone heat fluxes could not be calculated separately from water temperature data, it was possible to estimate the slag zone heat fluxes to be typically 60 kW/m^2 and from that to calculate the metal zone heat flux to be about 120 kW/m^2. The Waffle coolers were therefore designed for continuous operation at 100 kW/m^2 in the slag zone, and 500 kW/m^2 in the metal zone.

Detail design and materials procurement started in January 2002. The furnace was shut down prematurely due to a runout on 4 July and construction work started immediately thereafter.

9 COMMISSIONING AND RAMP-UP

Furnace preheating was completed on 23 August. By 26 August the power level was increased to about 20 MW and metal was first tapped on 27 August. By 30 August the power was raised to 25 MW and slowly increased to about 30 MW in the first week of September.

As would be expected bath sidewall heat fluxes steadily increased as the power level increased with average heat fluxes typically 120 kW/m^2 in the lower (metal plus slag) zone, and 60 kW/m^2 in the upper (slag plus freeboard) zone. The lower zone heat fluxes were increased significantly when higher metal levels occurred.

10 OPERATION

10.1 September 2002

By the end of September the power level was up to 35 MW and sidewall and freeboard temperatures exceeded 1600°C in open-bath operation. By this stage some loss of alumina-chrome rammable from the hot face of the Waffle coolers had occurred (Figures 5 and 6), and the equilibrium slag freeze lining in the upper slag and freeboard zones was reduced to 10-40 mm thickness. The Waffle coolers are able to maintain this freeze lining in the slag zone, which although occasionally suffering spalling, would heal itself when recontacted with molten slag. On occasion the open arc/freeboard heat flux on these exposed Waffle coolers measured locally up to 130 kW/m^2, and at times exceeded both the prevailing slag and metal bath sidewall heat fluxes.

By contrast, the freeboard sidewall refractories above the Waffle coolers could not develop a freeze layer and in the areas of most intense arc radiation were subject to thermal and chemical attack. To minimize excessive arc radiation on the freeboard sidewalls, the arc length was reduced so as to better contain this radiation within the zone of the Waffle coolers, which were better able to withstand the high heat fluxes.

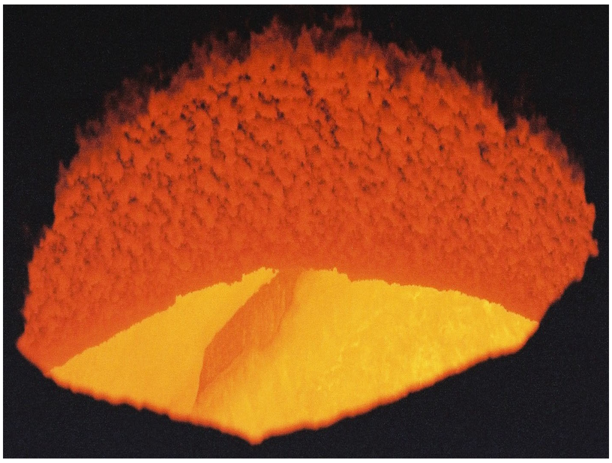


Figure 5. Loss of feed cover and refractory lining on a Waffle cooler

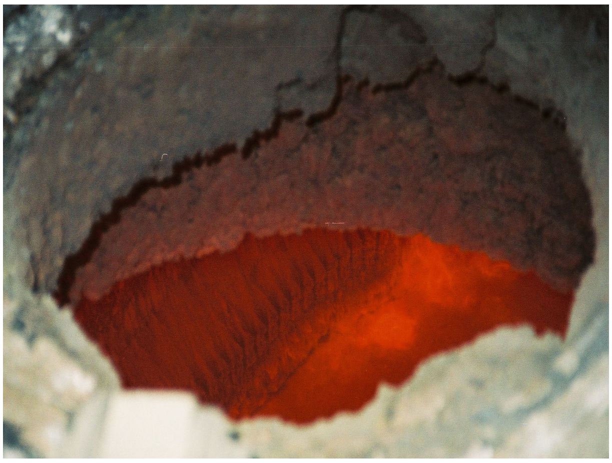


Figure 6. Appearance of erosion channels on the top of the Waffle cooler ledge, with liquid and solids slurry flow down exposed Waffle grooves

10.2 October 2002

A bath inspection on October 1, confirmed accelerated regional attack on the lower freeboard. The power input was immediately reduced to 25 MW, and the arc length was reduced to 300 mm irrespective of any increased bath stirring and associated higher heat fluxes to the Waffle coolers. Other changes were implemented in an attempt to limit further irreparable damage to the sidewall refractories, including addition of dust and an increase in the heterogenite ($CoOH(H_2O)_x$) in the feed from 5 to 7% by mass to provide a freeboard more opaque to arc radiation.

It became clear that while the Waffle coolers could operate at 35 MW at high slag levels and medium to long arcs (tested to a maximum arc current of 40 kA), the freeboard refractory design could not tolerate such sustained operation.

The furnace center feed pipes were relocated to feed even closer to the electrode in a further attempt to reduce freeboard arc radiation, though following this shutdown there was a steady increase in sidewall heat fluxes. There also appeared to be a build up of melting feed and “slag splash” on the top ledge of the coolers, as demonstrated by erosion channels observed in this build-up, ostensibly caused by a slurry melt flowing down the build-up (Figure 6).

The arc length was further reduced to 150 mm to reduce the heat load on the upper sidewalls. However this shorter arc also caused an increase in the bath sidewall heat flux in the slag bath zone. Evidence of stirring upward at the sidewalls led to postulation of an increased Lorentz force resulting from the increased electrode current (although a silicon reversion and CO boil mechanism developed later, may better explain the upward stirring observed at the sidewall copper coolers – Section 11.2). As a result a practical operating limit of 40 kA was placed on the electrode current, based on empirical observations. At this point the furnace operating strategy was forced to use the Waffle coolers to the maximum extent possible to minimize the arc/freeboard heat flux and limit upper sidewall refractory damage. This meant operation with a short, even immersed, arc and a thin slag (200 mm above the slag taphole). The furnace was also purposefully overfed to ensure a solid bath cover and banks at the sidewalls, in an effort to limit open-bath radiation to the freeboard refractories and bath stirring on the Waffle coolers (Figure 7).

From this point on, the furnace operation was increasingly being dictated by the deteriorating condition of the freeboard sidewall wall refractories which in turn resulted in higher heat fluxes in the metal zone and frequent alarms and trips of the coolers. High liquidus MgO-rich slag coating of the Waffle coolers was repeated as cooler heat fluxes approached the alarm limits and produced several short-term positive effects namely:

- Formed a protective coating on the coolers and lowered the copper block temperatures.
- Reduced the copper cooler heat losses by up to 50%.
- Lowered heat losses, resulting in demonstrably lower gross furnace specific energy consumption (SEC).

On 6 October, water was found to be leaking between the joint of the south alloy tapblock and adjacent cooler. The tapblock was decommissioned under controlled conditions by closing the water flow to circuit A of the dual cooling circuit of the tapblock to stop the leak. The furnace operation then continued with the south tapblock closed off and tapping operations continuing on only the north taphole. The decision to install a non-hydratable alumina-chrome refractory at the periphery of the hearth under the Waffle coolers was vindicated by this event, in that the resultant water leak did not cause any noticeable hydration of the hearth, or disruption to the operation.

The cause of the water leak is not known. Although there was no conclusive evidence that lance damage caused the water leak, there were signs that excessive lancing had been used to keep the metal flowing, and there was evidence of severe faceplate damage. A program to reinforce tapper training was then put in place to minimize the risk of a run out due to excessive lancing. The opportunity was also taken to replace the first 3 tapping module refractory bricks.

During October it was also noticed that there was significant skewing of the heat fluxes around the furnace, with the NE zone of the furnace freeboard exhibiting a considerably higher heat loss due to preferential upper sidewall refractory loss. A feed imbalance shifted this temporarily on one occasion to the SE, demonstrating the worth of the Waffle coolers to measure furnace heat fluxes (Figure 8), but this was rapidly remedied by repair of a faulty feeder. The directionality of the freeboard attack and generally higher sidewall and Waffle cooler heat fluxes observed in the NE zone of the furnace may possibly indicate a skewed anode attachment.

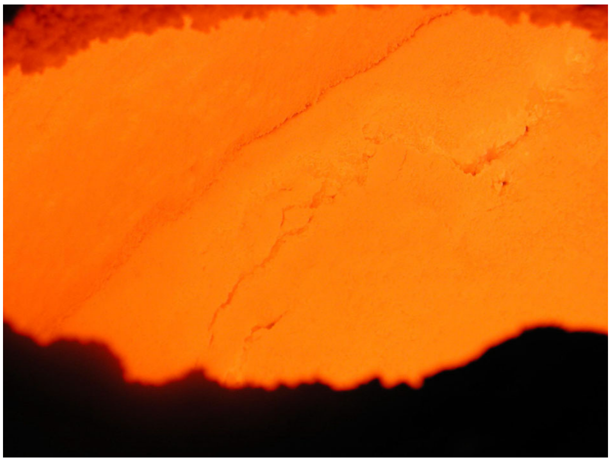


Figure 7. Operation with bath cover and a sidewall bank covering the Waffle cooler to limit bath stirring

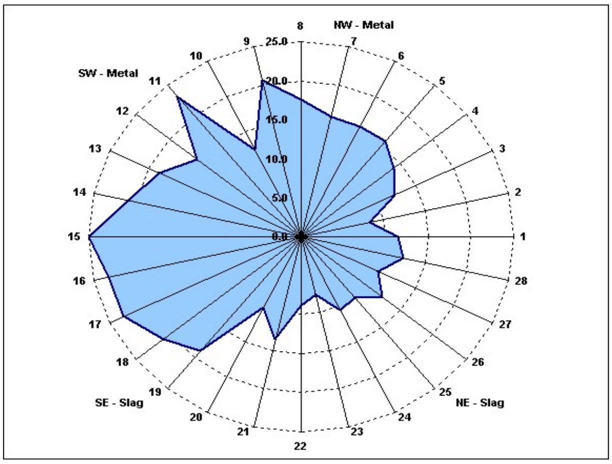


Figure 8. Impact of a blocked feeder on skewed cooler sidewall heat fluxes

During operation at 30 MW, one cooler experienced a high temperature alarm for which the calculated peak heat flux was about 1400 kW/m^2 – almost twice the maximum design heat flux. At the time the metal temperature was estimated to be 1750°C, i.e. about 300°C above the normal design temperature, and the metal levels were also higher than normal. The cooler responded favourably to lowering the metal level (Figure 9).

It was assumed that there had been significant loss of the freeze coating on this Waffle cooler and slag coating of the Waffle coolers down to the metal taphole was carried out to reform a protective coating. It was later discovered that raw materials contamination of caustic magnesia for magnesite resulted in a slag containing over 38% MgO and excessively high slag and metal temperatures.

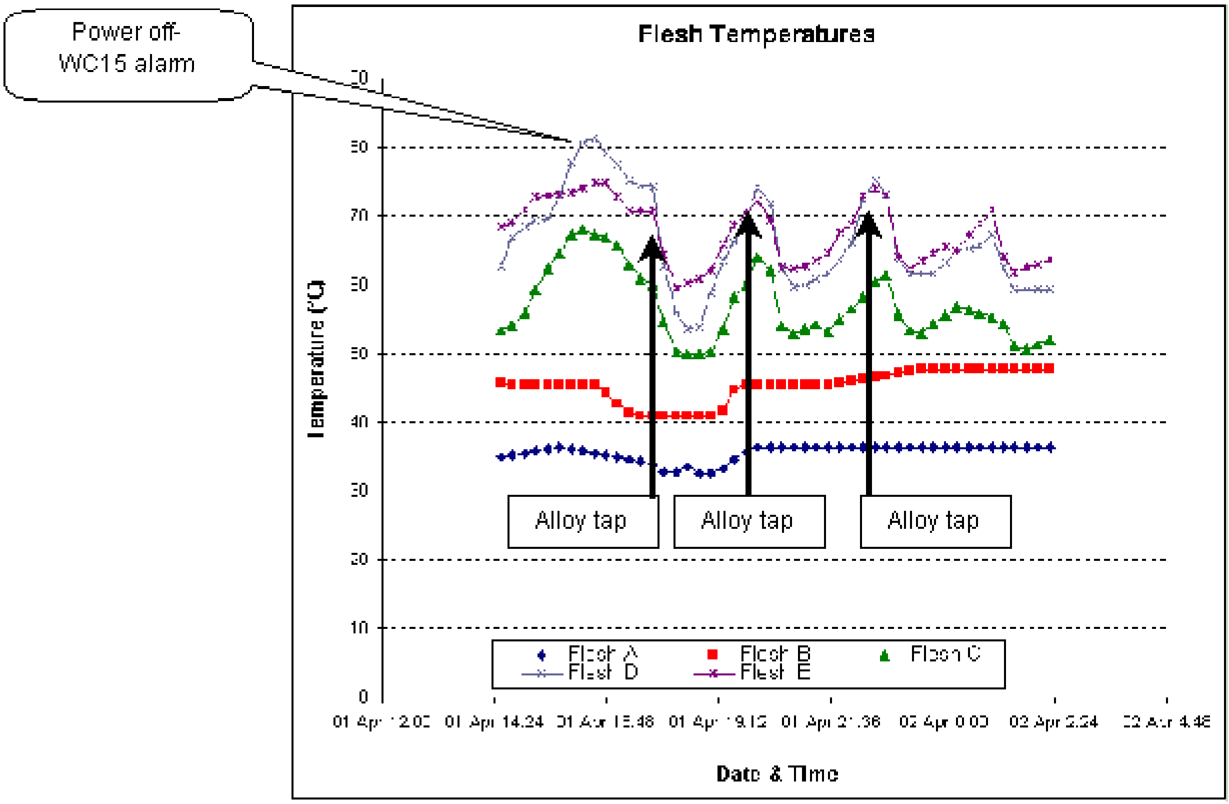


Figure 9. Response of lower Waffle cooler heat flux to alloy tapping

10.3 November 2002

The furnace continued to operate at a 30 MW set point with slightly over 80% availability on good weeks. Furnace downtimes were mainly due to high cooler temperatures, off-gas blockages, and feed system problems. Typical heat fluxes when the furnace operation was stable were in the range:

- 150 kW/m^2 in the lower cooler zone
- 40 kW/m^2 in the upper cooler zone, though excursions were common.

By the end of November Chambishi were able to operate the furnace at record throughputs with a best weekly average power of 30.9 MW, and though heat fluxes were higher they could generally be attributed to high metal levels and temperatures.

On 27 November the North taphole was being repaired when metal began to run out of the hole. Operators were unable to plug the hole with the clay gun and the furnace was drained. No major damage occurred and the taphole was then repaired and the furnace brought back into operation. The cause of the runout was determined to be insufficient cooling duration prior to breaking out the taphole.

10.4 December 2002 / January 2003

During December the average feed exceeded 1000 tpd with a daily best of 1174 t of feed. The power set point was progressively raised to 38 MW (yielding an average power of 34.4 MW) with an availability of 90%.

This was followed by a period of increased downtime caused by copper cooler alarms. This was thought to be due to operation with an immersed electrode and a thin slag layer which, due to stirring actions, caused some of the protective build up on the Waffles to come loose. Slag levels were then increased and the frequency of alarms reduced.

In the week ending 27 December the copper coolers caused only 2 minutes of downtime due to high temperature alarms. At this time offgas problems replaced the coolers as the major cause of downtime. Change from Hwange coal to Grootegeluk coal with a more consistent fixed carbon content occurred at this time in an effort to effect improved control over the process metallurgy and extents of cobalt and iron reduction especially.

On 28 December water appeared dripping from near the North taphole. The furnace was again shut down under controlled conditions, the tapblock was removed, and a spare block installed. From investigation of the tapblock after removal from the furnace it appeared that the tapping channel refractory had not been replaced before the taphole diameter had become too large at the hot face and that metal had evidently flowed directly in contact with parts of the Waffle copper surface. The opportunity was also taken at this time to repair some of the upper sidewall refractories by installing refractory curtains over the bare spots. Power was brought back on 3 January at around 20 MW and was up to 38 MW by 8 January.

Roof heat losses increased 20% following this repair, with greatest heat losses associated with the roof panels that were disturbed to install hung refractory curtains to protect the sidewall freeboard. This suggested spalling of the roof panel castable and cover had occurred; something that could not be repaired by conventional *in situ* slag splashing and furnace fuming with the immersed electrode mode of operation that prevailed.

10.5 February 2003

In early February the average operating power achieved was a new high of 34.6 MW, however cooler alarms and off-gas blockages resulted in regular power trips. Cooler alarms typically went away after metal taps (e.g., Figure 9), but to reduce the frequency of trips the operators raised the electrodes to keep the current below 40kA and below 35kA if at all possible. This, coupled with maintenance of a thick bath cover and sidewall feed banks (reductant-enriched), is believed to reduce metal stirring and lower the heat flux in the metal zone of the lower Waffle coolers. The average heat flux of all the coolers was erratic as power was turned off and on following alarms and trips with negative connotations on cooler performance, with peaks typically of:

- 170 kW/m^2 in the lower cooler (i.e., metal plus slag zone), and
- 80 kW/m^2 in the upper cooler (slag plus freeboard zone).

A feature of this period of operation was the struggle to create and maintain sidewall banks despite generally increased reduction levels, such as had been characteristic of the good period of production in November and December. This was possibly as a result of a greater reactivity of the new coal. Focus was also directed on the performance of the feeding system in an attempt to better control the feed recipe and the all important furnace feed-to-power ratio.

11 WAFFLE COOLER - PROCESS ISSUES

11.1 High Slag Superheat

Selective carbothermic reduction processes classically introduce inherent control difficulties [7]. At Chambishi, the highly acidic nature of the predominantly iron-bearing discard slag (50-55% SiO_2 and 13-14% total Fe) additionally complicates containment of the slag within conventional refractories due to:

- Direct chemical attack of the basic magnesia-C and alumina-chrome refractories of the hearth that are compatible with the alloy, and
- Inherent low slag liquidus (≈ 1150°C) that, when coupled with a required slag tapping temperature of at least 1550°C to ensure tapping of alloy above its 1370°C liquidus temperature, results in a slag superheat (ΔT) of about 400°C. This, coupled with the potentially high turbulence and bath stirring (promoting convective heat transfer, h) of a DC-arc furnace, directly contributes to an inordinately high process sidewall heatflux ($q_{s/w}$) , defined by:

$$q_{s/w} = h\Delta T \quad (1)$$

High sidewall heat fluxes in turn lead to thinned thermal equilibrium refractory or freeze-lining layers.

This specific character of the Chambishi slag largely dictated the conversion to high-intensity Hatch Waffle coolers that are capable of operating safely at high heat fluxes even with recoatable freeze linings thinner than 50mm thick [5].

11.2 Silicon Reversion and CO Boil

In addition to bath stirring phenomena peculiar to DC-arc furnaces, the Chambishi process was also found to impose two somewhat unexpected stirring phenomena, that further placed stress on the heat flux duty required of the Waffle coolers; namely:

- Vigorous upward stirring of the bath at the sidewall, even several hours after furnace shutdown (Figures 10-12).
- Vigorous upward bath stirring associated with cold alloy revert addition into the bath (Figure 13).

The phenomena are believed to be related, and involve a combination of exothermic silicon reversion and endothermic CO boil according to:

$\underline{Si} + 2/x\ FeO_x = SiO_2 + 2/xFe$ $\quad \Delta H°_{1600°C} = -2.980$ MWh/t Si (assuming x = 1) (2)

$\underline{C} + 1/x\ FeO_x = CO + 1/xFe$ $\quad \Delta H°_{1600°C} = +2.679$ MWh/t C (assuming x = 1) (3)

that lead to the observed thermal convection cells and even regular gas-stirred circulation (in the case of reaction (3)) at the Waffle cooler perimeter, and are capable of considerably aggravating local bath sidewall cooler heat fluxes.

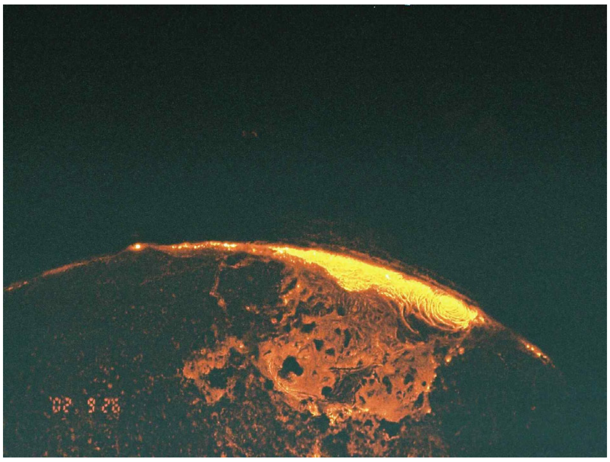


Figure 10. Evidence of upward convection cells at cooler perimeter, 6h into a shutdown to replace the roof with feedchutes better directed to the centre of the furnace

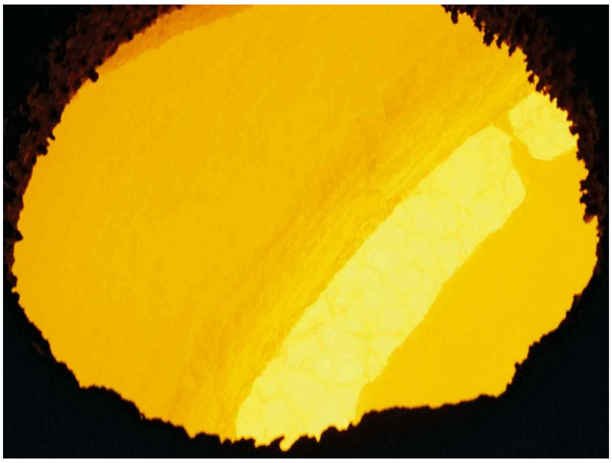


Figure 11. Global vigorous upward stirring adjacent to coolers at furnace perimeter, with evidence of rising gas bubbles

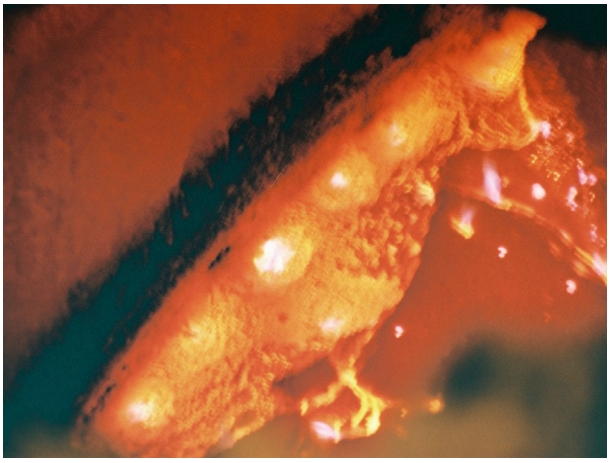


Figure 12. Upward welling and pulsing of hot liquid bath adjacent to coolers, 2h into a shutdown

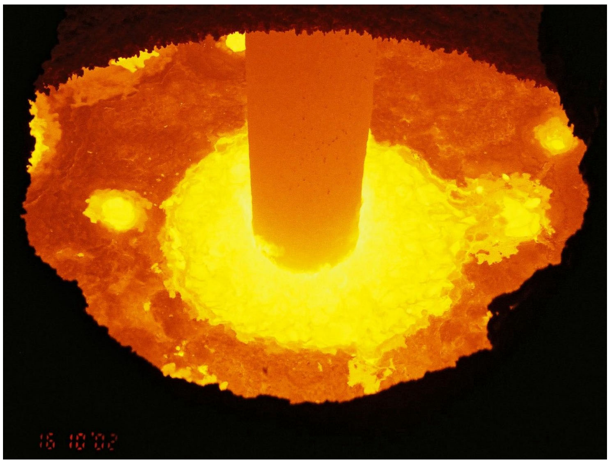


Figure 13. Vigorous upward stirring around electrode following reverts addition, 2h into a shutdown

The sources of the dissolved C and Si (firstly considering the absence of reverts addition) are postulated to be due to reactions promoted by high temperatures, especially in the vicinity of the hot electrode; namely:

$C = [C]\ (1\ wt\%)$ $\quad \Delta G° = 22593.6 - 40.58T$ kJ/mol (4)

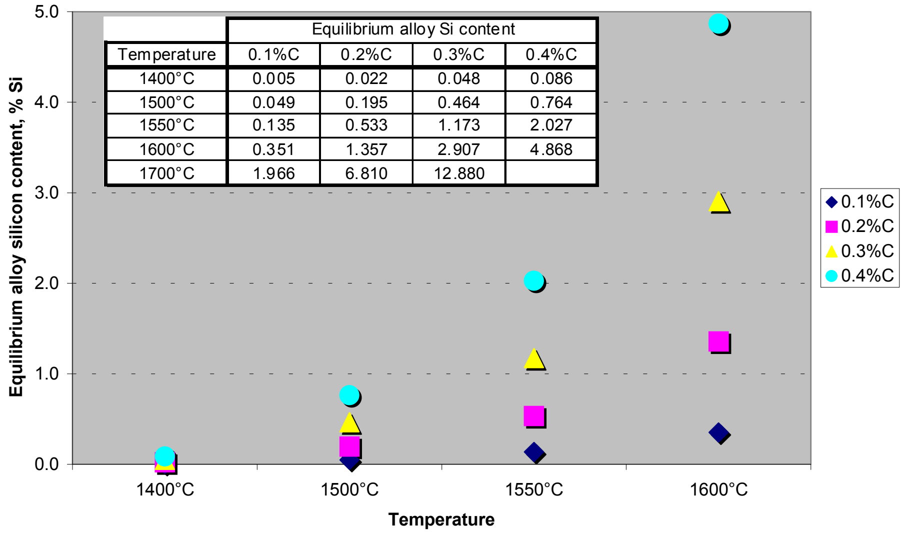
$SiO_2 + 2\underline{C} = \underline{Si} + 2CO$ $\quad \Delta H°_{1600°C} = 5.271$ MWh/t Si reduced (5)

Reaction (4) can be readily envisaged to proceed by dissolution of carbon into newly formed liquid ferroalloy produced under all practical process temperatures at either of the slag-reductant or slag-graphite electrode interfaces. Reaction (5) is highly endothermic and the extent of reaction is strongly temperature dependent. By considering liquid iron solvent and the dissolved 1 wt% reference state:

$$(SiO_2) + 2[C]\ (1\ wt\%) = [Si]\ (1\ wt\%) + 2CO \qquad \Delta G° = 544464 - 308.8T\ kJ/mol \qquad (6)$$

it is possible to estimate, in an iterative scheme, the alloy silicon content in local equilibrium with a given dissolved alloy carbon content (assuming published dissolved solute Co, Cu, C, S and S interaction parameters), as functions of temperature, slag silica activity and slag height (hydrostatic head affects prevailing local p_{CO}). This additionally shows that high alloy silicon content is also favoured by high alloy carbon content and low bath levels (Figures 14 and 15).

Further thermodynamic investigation of reaction (6) demonstrates that the local oxygen potential will be controlled by the alloy silicon content at temperatures lower than 1561°C and by the alloy carbon content at higher temperatures, for typical furnace conditions of an alloy composition of 0.16 % C and 0.46% Si located at, or near, the alloy-slag interface under an assumed slag bath of 1 m depth. Application of Le Chatelier's principle, also demonstrates that silicon reversion by reaction (2) will be promoted by lower temperatures (exothermic reversion reaction), while carbon refining by endothermic reaction (3) will be favoured by higher temperatures.



	Equilibrium alloy Si content			
Temperature	0.1%C	0.2%C	0.3%C	0.4%C
1400°C	0.005	0.022	0.048	0.086
1500°C	0.049	0.195	0.464	0.764
1550°C	0.135	0.533	1.173	2.027
1600°C	0.351	1.357	2.907	4.868
1700°C	1.966	6.810	12.880	

Figure 14. Plot of equilibrium alloy silicon content (mass %) predicted as functions of temperature and alloy carbon content

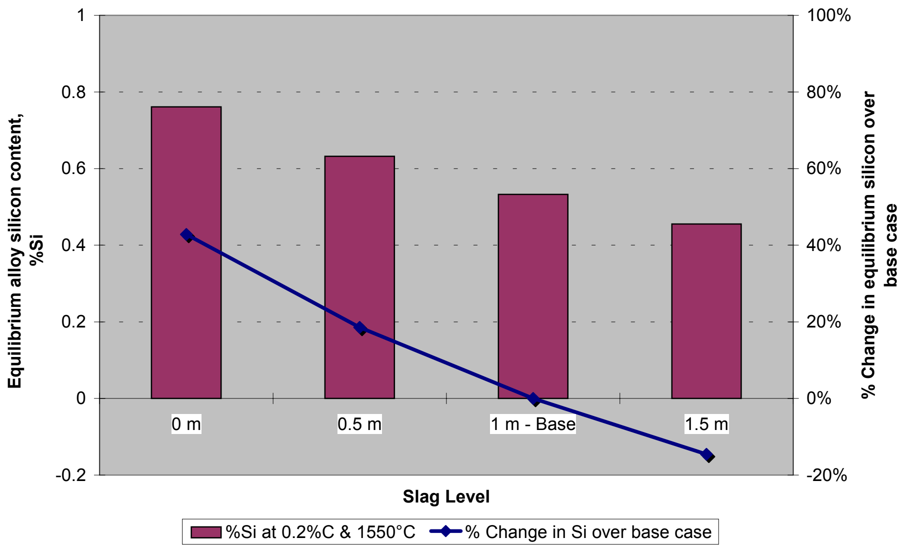


Figure 15. Influence of lowered p_{CO} through slag level on predicted equilibrium alloy silicon content at 0.2% C content and a temperature of 1550°C

It is now possible to postulate an explanation for the sustained upward sidewall stirring observed, as follows:

- Alloy droplets of high silicon content are produced by carbothermic reduction of abundant SiO_2 in the slag through a general reaction (5) and promoted by:
  - Locally hotter conditions; e.g., in vicinity of electrode, or in over-powered or under-fed furnace conditions
  - Locally more reducing conditions; e.g., again in the vicinity of the electrode
  - Use of reductants of higher liquid alloy reactivity (i.e., reductants exhibiting enhanced kinetics of carbon dissolution into alloy and typically possessing more ordered carbon structures and [8]) such as electrode graphite or high-rank anthracites, that can increase the carbon content locally of the alloy being produced, further raising the potential local equilibrium alloy silicon content
  - Lower p_{CO}, promoted by conditions where the bath is being tapped down and a lower hydrostatic head prevails.
- Especially if the electrode is deeply immersed, there will be limited opportunity for alloy silicon and carbon refining reactions (2) and (3) to proceed substantially.
- This leads to enhanced alloy silicon contents in the alloy locally under the electrode as alloy disengagement from slag occurs.
- Silicon-rich alloy migrates under concentration gradients, or by bath stirring, to the bath periphery.
- In contact with the cold cooler freeze lining, and especially if disturbed locally by addition of cold reverts feed, the local driving force for silicon reversion near the alloy-slag interface can become so high that reaction (2) proceeds spontaneously.
- Reaction exothermicity leads to local overheating, believed to be capable of inducing significant thermal convection cells and stirring.
- As silicon reversion proceeds, and temperatures rise, a condition can be reached locally where control of the oxygen potential switches to the dissolved carbon in the alloy. Provided that CO gas bubbles can nucleate, this can lead to a spontaneous CO boil by reaction (3) and associated gas bubble-driven circulation.
- The combination of hot conditions (exothermic silicon reversion) and vigorous stirring, is likely to lead to a significant rise in the bath sidewall cooler heat flux that the Waffle coolers must contend with.
- Potentially, it is conceivable that the local disturbance that initiates silicon reversion and a CO boil is capable of propagating itself into a global furnace condition of intense upward stirring around the entire sidewall perimeter.
- With significant cold revert addition, and especially in view of the postulated higher probable silicon potential in the region under the electrode, local cooling of the alloy by reverts may be expected to initiate silicon reversion, exothermically raise temperatures and ultimately upon silicon depletion, cause a significant carbon boil.

12 SUMMARY OF STATUS OF CURRENT OPERATION

The operators are currently adjusting furnace conditions to maintain the furnace operation at power levels approaching 35 MW, at weekly average smelting rates up to 1000 tpd (Figure 16). The general operating strategy aimed at protecting the upper sidewall, while minimising furnace trips due to high cooler temperatures is as follows:

- Operate with lower metal levels to reduce the heat load on the coolers, yet still maintaining a sufficient metal depth to limit slag contact of the tapping channel refractories (i.e., ideally ~200 mm).
- Operate at, or below, 35kA electrode current – believed to limit stirring and lower bath sidewall heat fluxes.
- Operate with bath cover and sidewall feed banks (containing reductant) to limit bath stirring.
- Operate with an immersed arc to reduce the heat load on the freeboard sidewalls and roof.
- Periodic slag coating with MgO to rebuild the freeze layer on the coolers.
- Focus on operational rhythm to limit local process instabilities that are believed to contribute to exothermic silicon reversion and associated CO boils that can promote undesirable bath sidewall heat fluxes especially at the important slag-alloy interface.
- Improve control diagnostic programs for setting power-to-feed ratios and raising alarm and trip settings of the coolers.

It is worth noting that the techniques for reducing the heat load and refractory erosion on the freeboard sidewalls generally result in an increase in the heat fluxes on the Waffle coolers. The challenge for the operator is to balance these conflicting needs to operate the furnace safely at its maximum throughput. Clearly an improved upper sidewall cooling design, possibly involving water-cooled copper plate coolers, would alleviate much of this constraint.

13 FUTURE MODIFICATIONS AND IMPROVEMENTS

It is currently planned to lower the metal taphole approximately 100 mm to allow operation with lower metal levels, higher slag covers and hence a less submerged electrode, and to improve the Waffle cover when performing periodic slag coating.

Means are also being sought to improve monitoring of cooler temperatures and to develop methods of measuring heat fluxes and of predicting the amount of freeze cover on the Waffles in localized areas of each cooler, to permit safe operation at even higher heat fluxes.

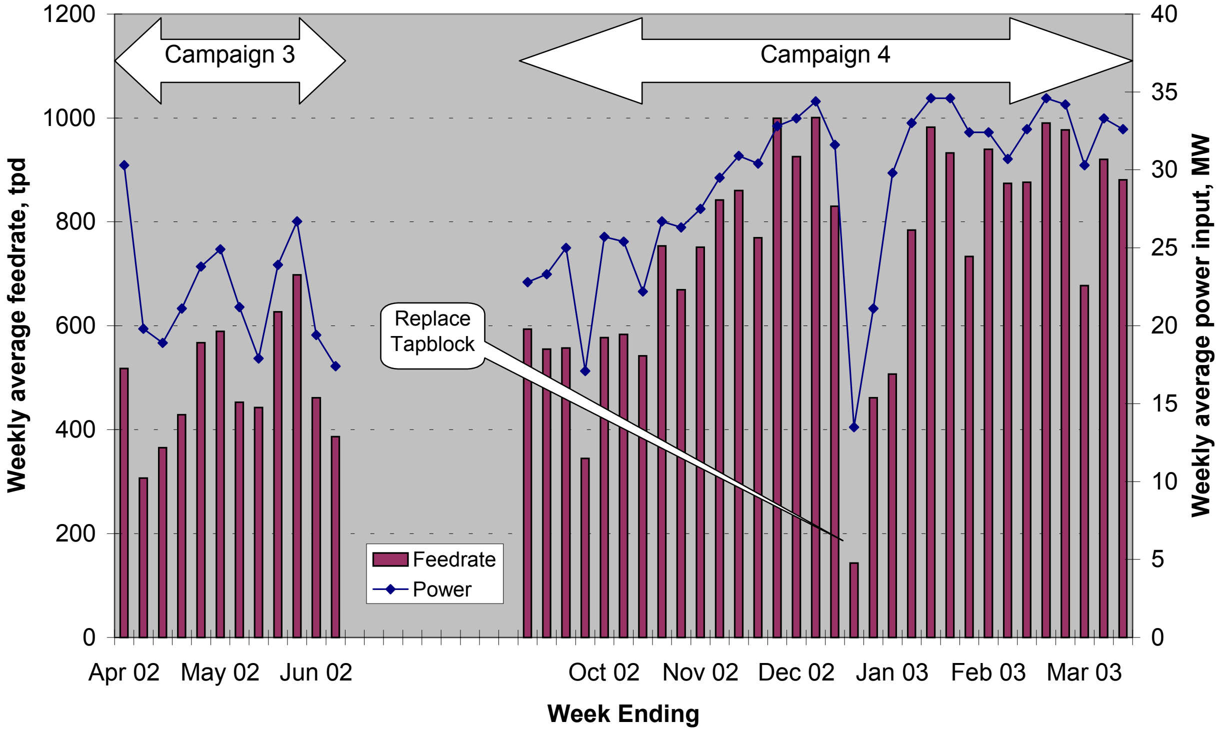


Figure 16. Plot of average power input (excluding periods of downtime) and daily smelting rate calculated over weekly periods showing the improved performance from Campaigns #3 to #4.

Possible process modifications are to reduce slag superheat by changing to a MgO-based fluxing practice, (while still maintaining 17% by mass total slag CaO plus MgO content). Issues preventing this currently relate to the availability and cost of a suitable flux source material and concerns that high slag MgO content may impact adversely on cobalt recoveries. A return to coal of lower liquid alloy reactivity (lower kinetics of carbon dissolution into the alloy) is also being considered to determine if it aids establishment and maintenance of sidewall banks. This may also yield a subsidiary benefit of simultaneously lowering carbon and silicon contents of the alloy, that at times are believed to contribute to undesirable silicon reversion and CO boil reactions. Means to improve the feed system accuracy to effect better control of the furnace feed and feed-to-power ratio are also being considered.

14 CONCLUSIONS

The Hatch sidewall Waffle coolers and tapblock appear able to withstand substantial heat fluxes under conditions where other traditional furnace lining designs have failed in three previous campaigns at Chambishi. The ability of the Waffle coolers and tapblock to directly withstand very high localized ferroalloy heat fluxes in excess of 1000 kW/m^2 in a DC-arc furnace smelting environment is a noteworthy first. An additional advantage of the application of well-instrumented Waffle coolers is that they provide excellent monitoring of furnace heat fluxes that permit improved interpretation of furnace operating and process conditions to guide the operators more safely through such thermal excursions.

The operating experience at Chambishi has also demonstrated that DC-arc furnace smelting presents a number of idiosyncrasies that must be addressed to maintain a continuous smelting operation. These include:

- Need for sidewalls and roof to withstand high arc and freeboard heat fluxes (measured instantaneously as high as 130 kW/m^2 on the Waffle coolers) in open-arc and open-bath operation
- Capability of the offgas system to operate without blocking at high temperatures and with reasonable dust and fume loading
- Difficulties centering the arc and arc attachment zone that can locally accelerate sidewall wear as a result of a combination of:
  - Possible arc column skewing and splashing of superheated and refractory-aggressive slags by long arcs
  - Possible skew arc attachment (related to apparent uneven current distribution through the conducting hearth and anode flags)
  - Periods of asymmetrical feed distribution, caused by feed imbalances through the four feedchutes peripheral to the electrode.

These items still require long-term resolution at Chambishi, and have forced development of a unique interim solution, involving an immersed DC-arc electrode mode of operation to limit sidewall and roof heat losses, and lower freeboard temperatures to avoid plugging of the offgas. The unfortunate consequence of the immersed electrode mode of operation is to increase the lower alloy heat flux to the Waffle coolers. Operation with substantial bath cover and unreacted feed banks at the Waffle coolers, concurrently limits freeboard heat flux and appears to limit bath sidewall stirring to partially counter excessive Waffle coolers heat fluxes. Periodic adjustment to a high liquidus temperature slag chemistry has also been introduced in order to rebuild a protective freeze lining on the cooler hot face and minimize the heat transfer rate to the Waffle coolers.

The Chambishi selective carbothermic reduction of cobalt oxide from slag is unusually complex from a purely process perspective. It introduces the following factors on control of the operation, and that can impact on the specific duty required of the Waffle coolers; namely:

- Even tighter control of the feed-power ratio is required to limit short term imbalances that can otherwise:
  - Rapidly raise process temperatures and magnify the already large slag superheat ($\Delta T = 400°C$) and so significantly increase bath sidewall heat fluxes
  - Drive unwanted endothermic side reactions especially in the vicinity of the hot immersed electrode that can:
    - Lead to fuming, such as of Mg(v) and SiO(v) species, that can contribute to offgas blockages
    - Increase local reduction of silica to silicon and drive carbon dissolution that can increase the potential for subsequent uncontrolled silicon reversion and carbon boil, so further raising the bath sidewall heat fluxes.
- Tight control of reduction extent and selection of appropriate reductant reactivity are important to ameliorate the requirements for high cobalt recoveries from the slag, while limiting carbon dissolution and silicon content locally in the alloy that may be susceptible to reversion and CO boil and maintaining a suitable bath cover with the presence of feed banks to limit freeboard heat fluxes and sidewall stirring.

Despite the inherent challenges, significant operational progress has been made at Chambishi since Campaign #3. In Campaign #4 weekly average smelting rates have almost been doubled (up to 1000 tpd), at weekly average power inputs approaching 35 MW.

15 ACKNOWLEDGEMENTS

This paper is published by permission of Anglovaal Mining Ltd. and Chambishi Metals plc. The authors acknowledge contributions of Chambishi operational staff, especially Adriaan van der Merwe, Watson Lumbwe and Gerbrand van Schalkwyk, and Andy Matyas, Laszlo Kadar, Floyd Botha and Derek Hayman of Hatch for valuable technical discussions and assistance.

16 REFERENCES

[1] Jones, R.T., Denton, G.M., Reynolds, Q.G., Parker, J.A.L., van Tonder, G.J.J., "Recovery of cobalt from slag in a DC arc furnace at Chambishi, Zambia", Copper Cobalt Nickel and Zinc Recovery Conference, SAIMM, Victoria Falls, Zimbabwe, 16 - 18 July, 2001.

[2] Munnik, E., Singh, H., Uys, T., Bellino, M., du Plessis, J., Fraser, K. and Harris, B., "Development and Implementation of a Novel Pressure Leach Process for the Recovery of Cobalt and Copper at Chambishi, Zambia", Recovery of Base Metals in Southern Africa Conference, SAIMM, Sun City, South Africa, 16 - 18 July, 2002.

[3] Bailey, C., Harris, G.B., Kuyvenhoven, R. and du Plessis, J., "Removal of Nickel from Cobalt Sulphate Electrolyte using ISEP Continuous Ion Exchange", Copper Cobalt Nickel and Zinc Recovery Conference, SAIMM, Victoria Falls, Zimbabwe, 16 - 18 July, 2001.

[4] de Vries, S., Voermann, N., Ma, T., Wasmund, B. O., Metric, J. and Kasinger, S., "Novel DC furnace design for smelting nickel and cobalt bearing concentrate from spent alumina catalyst",

[5] Sarvinis, J., de Vries, S., Joiner, K., van Mierlo, C., Voermann, N., Stober, F., Rule, C. and Majoko, P., "Improvements to BHP Hartley Platinum's Smelting Furnace", Proceedings of the Copper 99–Cobre 99 International Conference (TMS), October 1999, Phoenix, U.S.A.

[6] Voermann, N., Ham, F., Merry, J., Veenstra, R., Hutchinson, K., "Furnace Cooling Design for Modern High-Intensity Pyrometallurgical Processes", Proceedings of the Copper 99–Cobre 99 International Conference (TMS), October 1999, Phoenix, U.S.A.

[7] Nelson, L.R., "Determination of the possible causes of a foaming slag by its mineralogical and textural characterisation", Extraction and Processing for the Treatment and Minimisation of Wastes", Eds. Hager, J, et al., EPD-TMS, 1993, pp. 1041-62.

[8] Sahajwalla, V., Taylor, I.F., Wright, J.K. and Hardie, G.J., "Dissolution of carbon into iron melts : the new direct ironmaking perspective", Metallurgical Processes for the Early 21st Century, TMS, Ed. Sohn, H.Y., 1994, pp. 715-730.