COPPER CONVERTING AT BINDURA NICKEL CORPORATION USING AUSMELT TECHNOLOGY

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Abstract

Ausmelt Technology was selected by Bindura Nickel Corporation (BNC) as the basis for a new copper circuit to process nickel plant copper leach residue to blister, anode and finally cathode copper and recover PGM values at the Bindura Smelter Refinery (BSR).

The process selected, based on Ausmelt Technology to smelt and convert the residue to matte and blister copper and produce a discard slag, is novel incorporating smelting, converting and slag reduction process steps in a single Ausmelt vessel. The process demands a high quality blister copper product with low levels of arsenic and nickel.

This paper reviews the project and the initial operational results to the end of 1997 of the Ausmelt Top Submerged Lancing (TSL) smelter and discusses the implications for the wider TSL converter market.

Introduction

Bindura Nickel Corporation (BNC) operates several nickel/copper mines in Zimbabwe. It also owns a smelting and refining complex (BSR Ltd) at Bindura where it treats the concentrates from these mines.

Schwarz and Richardson[1] evaluated the options available to BSR to improve the recovery of gold, silver, PGM's, nickel and copper, and to improve the quality of the copper cathode produced. The process route chosen for the BSR improvement was a non-oxidative pressure leach on the existing leach circuit residue, followed by conversion of the resulting copper and PGM rich residue to copper anodes for subsequent electro-refining.

Sherritt Technologies supplied the non-oxidative pressure leach and Ausmelt Technology was selected to convert the residue to blister copper. A small induction anode furnace was also included by BNC to produce anodes for electro-refining.

In 1992, Ausmelt completed a laboratory and prefeasibility design study on the use of Ausmelt Technology for smelting and converting of the leach residue. The composition of the leach residue is shown in Table I.

Table I. Leach Residue Analysis.

		Typical	Range			Typical
Ni	wt%	0.75	0.2-1.0	Sb	ppm	100
Cu	wt%	70.0	70.0-74.0	Bi	ppm	20
Co	ppm	150	100-250	Pb	ppm	1100
Fe	wt%	0.1	0.05-0.30	Se	ppm	3500
As	ppm	3000	2500-3500	Ag	ppm	490
S	wt%	19.5	18-21	Te	ppm	390
H_2O	wt%	25	20-30			

In order to produce a saleable copper product, it was necessary to ensure the reduction of the arsenic and nickel levels in the copper residue during smelting and converting to $\leq$0.1% As and $\leq$0.5% Ni in blister copper. The laboratory study demonstrated that this could be achieved in an Ausmelt system.

The residue contains very low levels of iron. Pyrite was added to the process feed as flux to produce a suitable slag, and to assist in the volatilisation of arsenic. The pyrite composition is shown in Table II.

Table II. Pyrite Analysis.

	wt%		ppm
Cu	0.004	Na_2O	500
Ni	0.0095	K_2O	200
Fe	41.0	As	30
SiO_2	9.0	Pb	90
CaO	0.8	Se	3
S	42.0	Te	2
Al_2O_3	3.1	Bi	2
MgO	0.6	Sb	10
H_2O	1.0		

Coal from the Hwange Colliery, “Wankie coal” was to be used as both fuel and reductant for the smelting, converting and reduction operations. The composition of the coal is shown in Table III.

Table III. Coal Analysis.

	Unit	Value
Sizing	Mm	-12.70 + 6.35
Fixed Carbon	wt%	63.2
Volatile Matter	wt%	20.7
Sulphur	wt%	2.4
Phosphorus	wt%	0.023
Moisture	wt%	0.1
Calorific Value	MJ/kg	29.16
Ash Content	wt%	16.0
Ash Analysis:		
FeO	wt%	14.8
CaO	wt%	5.3
MgO	wt%	0.7
Al_2O_3	wt%	27.1
SiO_2	wt%	43.1

The first stage of the laboratory testwork investigated direct oxidative smelting of the residue to produce blister copper. This process route was unable to achieve the arsenic removal required, and the nickel could only be removed via the use of a large slag volume.

The testwork then examined a two-stage process of smelting under neutral or reducing conditions followed by converting of the matte product. The smelting stage thus ensured effective removal of arsenic as vaporised species in the offgas. Controlled over-oxidation of the matte then produced a blister copper containing less than 0.5% nickel. The over-oxidation removed nickel from the blister copper as nickel oxide in the slag. This produced a highly oxidised slag containing high levels of copper oxide (≈15% Cu).

A plant was then designed in the prefeasibility study to process 8,800 dry tonnes per annum of residue, containing 25% moisture. In this study, the smelting stage of the proposed process allowed production of a discard slag and a high-grade matte (≈75% Cu) by operating under reducing conditions. After tapping of discard slag, the matte product would then be converted in the furnace under strongly oxidising conditions to produce a blister copper containing ≤0.5% Ni and ≤0.1% As. The blister and oxidised converter slag would then be tapped respectively for further processing in an anode furnace for refining of copper and in the main electric smelting furnace for slag metal value recovery. Some converter slag would remain in the furnace as a heel to allow initiation of the next cycle of residue smelting.

Following this study, further discussions were held and the design was modified to allow production of 5,000 tonnes per annum of blister copper containing ≤0.6% Ni and ≤0.25% As from residue containing up to 1% Ni and 0.35% As. The design minimum direct yield of copper was 85%. After blister tapping, the slag would be reduced prior to tapping all except a heel of slag from the furnace and the nickel-copper alloy would be transferred by ladle to the main smelter electric furnace or Peirce-Smith converters as appropriate.

Design Process Description

The process flowsheet as designed is shown in Figure 1.

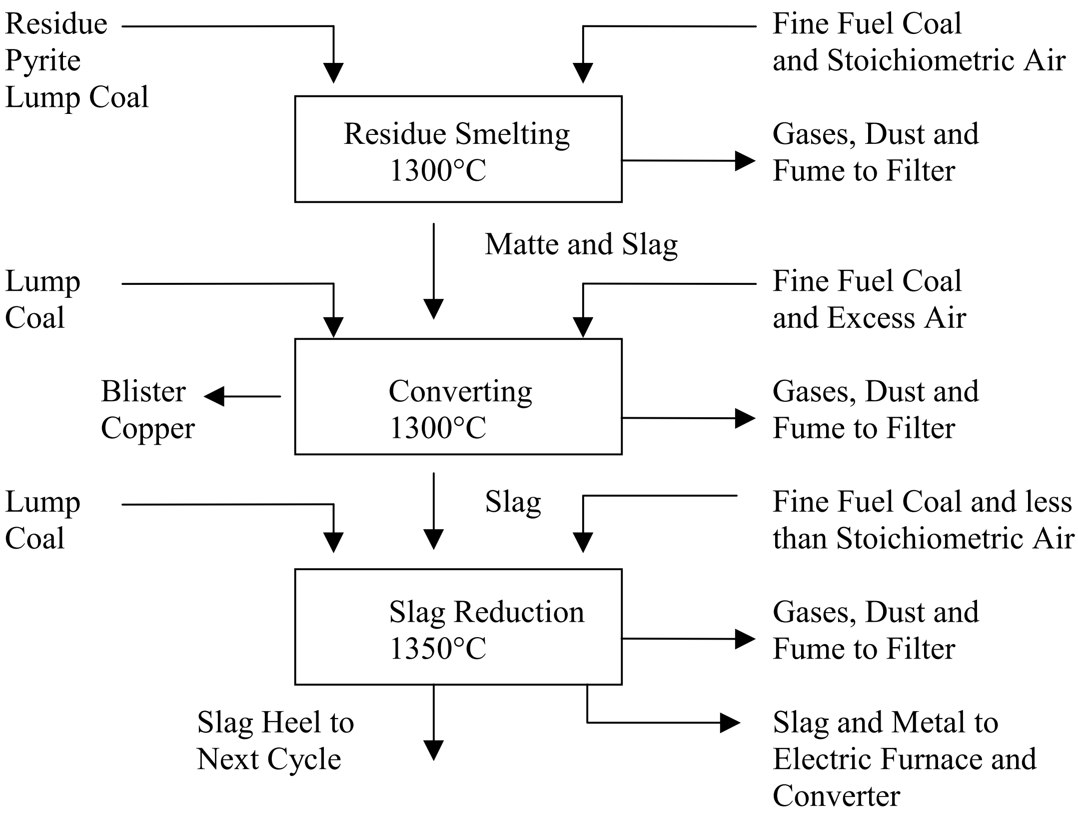

Figure 1: Process Flowsheet

Residue Smelting

The copper residue and pyrite are agglomerated in a pugmill to minimise feed carryover to the offgas stream and to facilitate feed capture to the bath.

Copper residue is smelted with pyrite and a small quantity of reductant coal in the Ausmelt furnace at a temperature of 1300°C. The energy requirements of the process are provided by the combustion of milled Wankie coal injected, along with combustion air, via the Ausmelt lance. The combination of reductant coal and pyrite creates conditions which allow arsenic to be removed as arsenic-sulphur compounds by volatilisation. The decomposition of the pyrite (FeS_2) to pyrrhotite (FeS) liberates sulphur which facilitates this step. The pyrite also prevents the formation of metal during the smelting stage. Metal acts as a sink for arsenic as compared with matte by lowering its activity. The arsenic compounds and reductant coal volatiles are oxidised in the upper regions of the furnace to produce arsenic oxides by air injected above the bath via the Ausmelt lance.

The copper, nickel and iron sulphides form a matte phase in which the PGM's concentrate. A controlled amount of excess air injected via the Ausmelt lance oxidises 60-70% of the iron sulphide to iron oxide, which combines with the SiO_2, CaO, Al_2O_3 and MgO components of the feed mix and coal ash to form a fluid slag.

The smelting continues until the furnace reaches its design capacity, which for this application is a total bath depth of one metre (1.0 m).

Matte Converting

At the completion of the residue smelting stage the furnace contains approximately 1.0 m depth of matte and slag.

The matte is converted to blister copper with air injected via the Ausmelt lance. The oxidation of the iron and copper sulphides supplies sufficient energy for this process stage to be operated without fuel over the 1.25 hours allowed for the conversion operation. A small quantity of reductant coal is added during the conversion to control the copper oxide and magnetite levels of slag to reasonable limits ($\leq$15% Cu, 25% Fe_3O_4).

The converting process is continued slightly beyond the normal blister copper end point, with the aim of oxidising the nickel from the blister copper to the slag with a target level of $\leq$0.6% Ni in blister. This over oxidation also oxidises a significant quantity of copper to the slag.

At the completion of the converting operation the blister copper is tapped from a hearth level taphole into the electro-induction anode furnace via a launder.

Slag Reduction

After the blister copper is tapped at the completion of the converting stage the slag remaining in the furnace contains significant levels of copper (4-16%) and nickel (0.3 - 1.1%). This slag is reduced with lump coal under reducing lance tip conditions at 1350°C for 1.5 hours. This produces an alloy of copper and nickel and a slag containing $\leq$0.6% Cu. During plant commissioning it was determined that the blister copper tap could be delayed until approximately half way through the slag reduction. This maximises the direct recovery of copper to blister, without compromising the nickel alloy production step.

At the completion of slag reduction the copper-nickel alloy is tapped through a hearth level taphole into a ladle for transfer to the existing converters. The slag is then tapped from a taphole located 200 mm above the furnace hearth into a ladle for transfer to the existing electric arc nickel smelting furnace. This step reduces the Ausmelt furnace copper and nickel levels and utilises the existing nickel smelter slag granulation system for slag discard, obviating the need for additional granulation facilities to be included in the Ausmelt plant.

The 200 mm heel of slag remaining in the furnace at the completion of the slag tap is used as the starting slag bath to allow the next cycle of residue smelting to commence.

Project Implementation

BSR contracted Ausmelt to provide the basic design of the smelting system and the detailed design of the furnace package. The detailed design and supply of the equipment outside of the furnace package was provided by others as part of the overall contract managed by Techpro, United Kingdom on behalf of BSR. Ausmelt also provided lances, supervision of design and installation of Ausmelt equipment by the construction engineers contracted to BSR in Zimbabwe and the licence to operate the plant. Training and commissioning supervision were also provided by Ausmelt. The final design report was submitted to BSR in April, 1993.

The installation of the plant in the existing smelter building at BSR was completed in May 1995.

Figure 2 shows a general arrangement sectional drawing of the furnace and building. The furnace is 2.2 m internal diameter and is lined with chrome-magnesite refractory bricks backed by a high thermal conductivity base within a shower-cooled steel cylindrical shell.

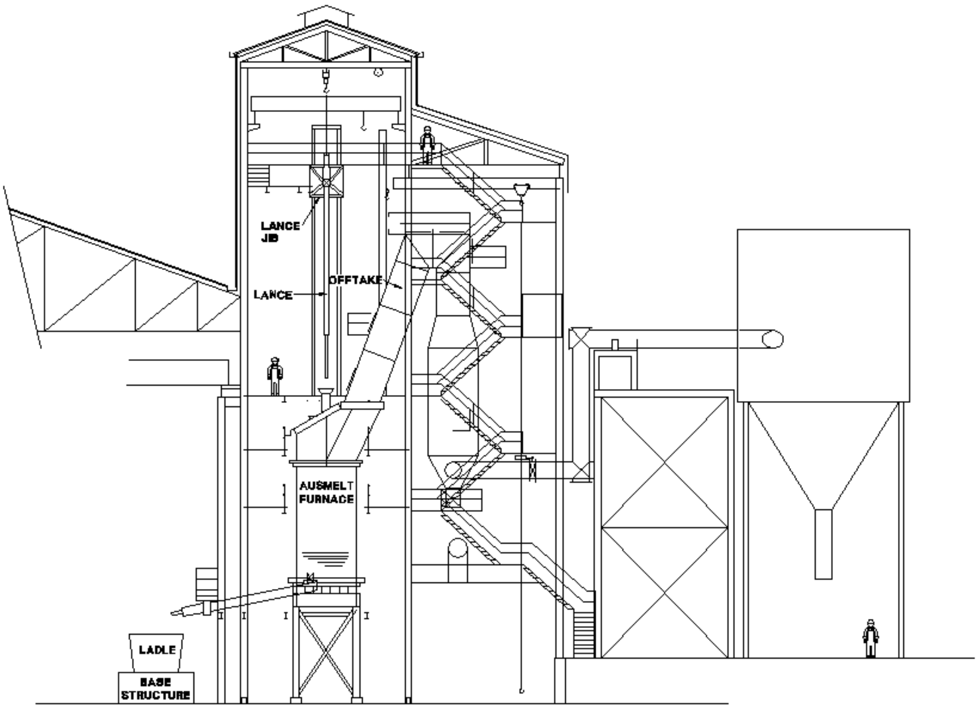

Figure 2 – General Arrangement Drawing of Furnace and Building

Commissioning

Hot commissioning of the plant commenced in May 1995. The smelting and converting operations were established in June 1995. Ausmelt supervision of the commissioning continued to late July to assist with process development and optimisation, particularly of the converting stage. During this period 36 charges were completed, smelting a total of 400 wet tonnes of residue. Blister copper produced was well within specification for arsenic, nickel, iron and sulphur. A consistent operating regime was established with plant operators becoming proficient at operating the plant without Ausmelt supervision.

A discard slag level of 0.6% copper was routinely achieved in the commissioning phase. The routing of this slag to the nickel smelting furnace allowed a relaxation of this operating parameter to the region of 2% copper with a view to reduce batch cycle times and maximise plant output.

The contractually required performance trial was successfully carried out, after a brief furnace shutdown for refractory maintenance and minor plant modifications, in September, 1995.

Typical assays achieved in commissioning operations are shown in Table IV.

Table IV. Typical Assays of Products by Stage.

		Design	Actual
Blister Copper	% Cu	97.5	98.66
	% Ni	0.6	0.3
	ppm As	741	2200*
	ppm S	1000	357
	% Fe	0.3	0.02
Cu/Ni Alloy	% Cu	86.9	94.55
	% Ni	4.9	0.58
	ppm As	7.2	0.03
	ppm S	0.6	0.67
Slag	% Cu	0.6	2.11
	% Ni	0.2	0.36

** High due to the residue containing significantly higher As than specified.*

Process Development

The smelter operation has developed from commissioning through the plant work up phase to current operational status.

Since start up, over the period September 1995 to March 1997, when a project upgrade commenced, operations have been characterised by the following:

- Process operations generally as per the metallurgical design.
- Product quality and productivity levels generally as per the design on a cycle and short-term basis.
- Annual throughput less than design due to problems with high refractory downtime and offtake duct chokes which adversely affected plant availability.
- Annual throughput less than design due to operating and equipment issues outside the Ausmelt furnace.

In 1997, a US$0.7 million development programme was undertaken to improve plant availability.

The specific availability and process throughput developments included:

- Pugmill unit modifications to provide improved feed agglomeration
- Quick connect assembly for lance installed
- Schenck loss in weight (LIW) coal weighing and feeding system installed
- Overhead crane and support structure for offtake duct removal erected
- Spare offtake ducts constructed

<u>Process Operation</u>

The process has proved relatively easy to operate with steady, replicable operations and a low level of process excursion considering the novelty of the operating process at commercial scale and a high turnover of operating and technical staff.

The BSR operations team and technical support staff were trained initially in classroom sessions and then during the commissioning phase by Ausmelt technical personnel. Thereafter, operations and throughput gradually improved as crews became familiar with plant operations and overcame specific problems.

In routine operations, the general level of performance summarised in Table V was achieved in the operating period 1995-1996.

Table V. Metallurgical Performance Data.

Smelting time:	7 hours 15 min
Converting time:	2 hours 30 min
Slag reduction time:	1 hour 20 min
Average cycle time:	12 hours
Batch size:	12.5 tonnes
Blister copper produced per batch:	8.6 tonnes
Blow time:	20 min/tonne of blister copper
Oxygen utilisation:	79.1%
Convert air flow rate:	5,500 Nm^3/hour
Refractory consumption:	19.6 kg mag – chrome bricks/tonne of blister copper
Plant availability:	50-75%, average – 60%.

The plant operations were not without start up problems. These were largely associated with equipment outside of the Ausmelt furnace package.

The plant downtime over the period 1995-1996 is shown in Table VI.

Table VI. Smelter Downtime Analysis.

	% Total Time
Duct change	10.64
Reline	11.66
Fuel coal	6.25
Anode furnace	4.20
Lance system	1.82
High angle conveyor	3.00
Feed system	0.85
Air supply	0.94
Cooling water	1.05
Pugmill	0.55
Others	6.97
Total	47.93

The total smelter availability for smelting of feed was in excess of 57%, excluding downtime in the above table for the anode furnace, casting system and non availability of feed.

The major specific operating issues which have arisen since start up are reviewed in the following sections by process area, and where relevant, by specific piece of process equipment.

Feed Handling System

Pugmill

The pugmill as supplied was inadequately engineered to process the design rate of leach plant residue.

This was due essentially to two basic reasons:

(a) Corrosion of the system from moisture added to agglomerate the feed caused rapid mixer wear and subsequent extended downtime;
(b) Engineering specification of the unit was below the required level for design throughput and material type and solids build up in the unit resulted in damage to the mechanical drive system.

The original unit was modified to keep feed away from the end bearings and more wear-resistant lifters were installed. Resultant beneficial effects on plant throughput and plant availability are apparent. While yet to be fully evaluated there appears to be a reduced incidence of offtake duct blockage which had been attributed to excessive carry-over of fine dry feed while the pugmill was out of service.

High Angle Conveyor (HAC)

The main feed conveyor to the furnace is a High Angle Conveyor (HAC) which squeezes the feed between two sections of conveyor belt. Due to the lumpy feed material occasionally experienced, spillage causing the belt to run off centre with subsequent plant downtime, was a significant feature of operations.

This problem has been recently overcome by ensuring that lumpy feed material entering the feed handling system is minimised and by paying particular attention to maintaining belt tracking which collectively have minimised belt tears and subsequent downtime.

Drag Link Conveyor

This unit was designed to feed material into the Ausmelt furnace with minimum ingress of air. It proved mechanically unreliable and has since been replaced with a simple chute arrangement with flap gate to form a gas seal.

Fuel Coal Feed System

The coal preparation and transport system has worked in a generally satisfactory manner. However, recent improvements introduced include a loss-in-weight Schenck weighing system which has substantially improved the apparent combustion efficiency of the coal-fired lance with a corresponding improvement in the overall process cycle time such that two full cycles on average are achieved in routine operations each 24 hours.

As initially installed, the system incorporated a belt weigh feeder for coal weighing and transport. This proved less than ideal, with occasional oversupply of fuel to the lance due to the incorrect belt weigher inputs to the control system generating an over-supply response. This gave rise to unsteady lance coal combustion and brief flame egress from the furnace roof ports. This problem has been resolved with the introduction of the Schenck loss in weight fuel metering system.

Furnace Performance

Furnace cycle time and blister copper production have been in line with, though generally in unfavourable variance to design, resulting in the operating parameters in 1995/96 as shown previously. Annual plant throughput and blister copper output have been below target for a number of reasons including a periodic shortage of suitable feedstock.

Lance operation with coal as fuel has proven successful after initial commissioning problems with moisture in fuel carrier air were overcome by the use of suitable moisture traps.

The lances have proven durable with each lance requiring minor tip repair after 1-3 cycles. The lances are repaired in the vertical lance park adjacent to the furnace operating floor.

The blister copper end point is determined by a combination of SO_2 offtake gas measurement and inspection of the copper sample in a traditional manner. The SO_2 analyser provides a trend of SO_2 gas strength rather than an absolute measurement. This has proven to be ideal for end point determination.

Process downtime caused by offtake duct chokes, and relatively high refractory wear have had an adverse effect on annual plant availability.

Offtake Build Up

Routine offtake duct blockages have occurred due to fine, dry feed material being carried out of the system, flash smelting to copper metal in the duct and generally blocking the offtake section at major gas flow trajectory changes.

This problem was exacerbated shortly after commissioning when the pugmill became inoperative and was subsequently removed from service for an extended period (late 1995 to early 1997).

Since the reintroduction of the pugmill in early 1997, the incidence of duct build up has substantially reduced. The build up is managed on a routine basis by replacing the ducts following the installation of an overhead crane system. This now occurs approximately every 35 days, up from a period of 14-18 days generally obtained over the period 1995/96.

Refractory Life

Refractory consumption has been high over 1995/96 with campaign lives varying in length up to approximately 90 cycles. There are a number of contributing factors to this. Firstly, the process cycle covers a varying range of conditions and operating regimes from highly oxidising to strongly reducing at temperatures from 1250°C to 1350°C. The highest refractory wear appears to occur in the final stage of the converting step with maximum slag activity and maximum copper in slag levels (≈15% Cu).

In recent campaigns during 1997, a higher quality refractory has been used in the high wear area with encouraging results. Campaign lives have increased by 100% to approximately 180 cycles and campaigns of greater than three months operating time are now experienced.

Anode Furnace

An electric induction furnace was installed as an anode furnace in the BSR flowsheet. Problems encountered in successfully processing blister copper to anode in this furnace necessitated the installation of a horizontal rotary anode furnace located adjacent to the converter aisle and fed with blister copper from the Ausmelt furnace via ladle and overhead crane in the main smelter aisle.

Anode Casting

A simple system incorporating a wheel with eight anode moulds, manual single spoon casting operation with manually operated hoist removal of anodes is used.

A steep learning curve for operators to maintain operations within the tight control band required for good anode production initially resulted in poor quality anodes. Acceptable quality anodes are now produced routinely.

Gas Handling System

Evaporative Gas Cooler

The evaporative gas cooler has worked satisfactorily. Minor build ups have occurred on and around the sprays, but have not caused any significant downtime.

The Sonicore unit successfully cools the gas from ±1150-1200°C to 350°C.

Ceramic Filter

The ceramic filter baghouse has essentially not operated since start up. The ceramic filter “candles” performed satisfactorily at temperatures up to 450°C. The major contributing factor to the failure to-date appears to be controlling the reverse gas cleaning system. Dust laden gas was directed to the clean side of the candles on numerous occasions, which resulted in the filters becoming clogged with dust and eventually blinding.

Operations Summary

The plant has performed largely to metallurgical and process design and has met the complex metallurgical demands placed on it in performing three very different process steps; copper smelting, converting and slag reduction in a single vessel.

The quality of the blister copper is as per design when taking into account variance in feed assays. Discard slags containing approximately 0.6% copper have been successfully demonstrated, however, the slag reduction process time has been reduced to reduce cycle time and increase plant throughput, and a final discard slag assay of 2% Cu is currently achieved. This slag is recycled to the electric furnace in the nickel smelting circuit for final recovery of copper and nickel.

The key Ausmelt Technology process step of converting of matte to blister copper has proved successful in:

- Achieving the process design performance parameters in 1995/96 shown in Table V.
- Substantially improving the process design performance parameters in 1997 as shown in Table VII.
- Demonstrating replicability and consistency in the process operation with less upset conditions then equivalent Peirce-Smith operations
- Demonstrating ease of operation with consistent levels of performance and productivity achieved despite a high turnover of operations and technical staff.

Future Development - BSR

It is apparent that plant operating performance has improved substantially since modifications were made to various plant sections in early 1997.

Process developments will continue to focus on incremental improvement to increase throughput and increase refractory campaign life.

Ausmelt is continually undertaking a review of its engineering designs and incorporates lessons from operating plants which will in due course feed through to all users of the technology to the general benefit of plant operators.

Developments occurring in other Ausmelt Technology plants which could reasonably be expected to benefit the BSR operation include:

- cooling finger installations
- developments from Ausmelt partnering arrangements with refractory manufacturers
- developments from Ausmelt technical associations with leading companies in the fields of furnace containment and gas handling.

Future Developments of Ausmelt Technology

The key outcome for Ausmelt, apart from the generally successful operation of a fairly complex metallurgical process based on Ausmelt Technology, is the successful demonstration at commercial scale of the Ausmelt copper converter.

The benefits of the Ausmelt converter are essentially:

- the same metallurgy as in standard Peirce-Smith copper converters
- the furnace is totally enclosed resulting in minimal fume emissions
- the enclosed furnace provides for minimal air ingress into the offgas thus maximising SO_2 content.

While the productivity indices of Table VI are not comparable to the most productive Peirce-Smith converters, they are creditable for a small scale unit of this type. The oxygen efficiency in the converting step is 85% which is an encouraging result.

Productivity levels comparable to, or better than modern Peirce-Smith converters will be achieved with this general level of oxygen efficiency at large scale.

Ausmelt Technology lends itself to replacement of existing Peirce Smith converters or for incorporation into new greenfield smelters and can successfully process molten and solid (granulated) matte.

Greenfield Smelter Operations

The first medium-large scale Ausmelt Technology operation incorporating a separate converting step in an Ausmelt furnace will come on stream in mid 1998 at Zhong Tiao Shan smelter, Shanxi Province in The People's Republic of China.

The general arrangement of the primary smelting, settling and converting furnaces is shown in figure 3.

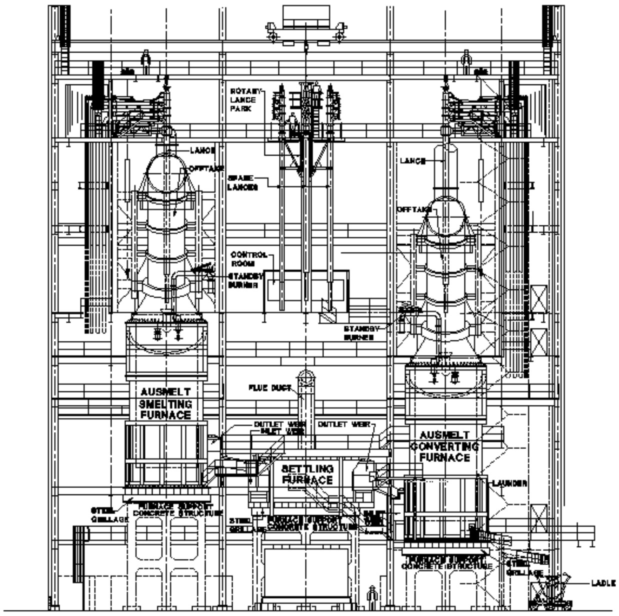

Figure 3 – General Arrangement of Primary Smelting, Settling and Converting Furnaces

Matte and slag from the smelt step will flow via weir and launder into the settler for separation. The high-grade matte (60-65% Cu) will be periodically drawn via weir and launder into the Ausmelt converter. The converter cycle will operate in a semi-continuous manner. The high-grade matte will be converted to white metal continuously as matte flows into the converting unit to fill it to the 1.0 m level. Once the normal operating level has been reached the matte inflow is stopped and the converting process is continued until blister copper is produced.

Oxygen enrichment is not used and the heat balance indicates cooling via solid copper addition will not be required. SO_2 offgas strength will be approximately 11.0%. The annual blister copper production is designed at 50,000 tonnes and the design converter productivity is 6.0 minutes per tonne blister copper produced.

This design is based on molten matte feed from the settling furnace to the converting furnace. However, it will also process solid granulated matte produced over periods when the convert furnace is out of operation for refractory repair.

Refractory life is anticipated at six months per campaign. External cooling fingers may be added at a later date, should operating experience indicate that this step would prove cost effective.

The heat balance of a converter unit processing granulated matte approximates that of a primary smelting unit, and advantages of this type of operation over molten matte feed include:

- true continuous operation possible
- oxygen enrichment possible with corresponding high-grade SO_2 offgas
- true disconnect between primary and converter smelting units.

Large-Scale Operations - 150,000 tpa Copper

The precise operational configuration of furnaces at the large-scale has not been confirmed.

Essentially, a single large (4 m ID) furnace utilising oxygen enrichment could process up to 300,000 tpa high-grade matte to produce blister copper.

External cooling will be required to provide satisfactory campaign life. It is also probable that the top of the furnace and the offgas sections will form part of a boiler system.

Similar systems are in operation in the steel industry and at face value would seem to provide a suitable concept for long term operational integrity.

Utilising the probable operating parameters of such a design provides the following target converter process parameters:

- 3 minutes per tonne blister copper converter productivity index
- 20% SO_2 offgas
- 80% oxygen efficiency.

Brownfield Smelter Operations

Ausmelt Technology converters should prove of interest to existing smelter operations which have Peirce-Smith converters and wish to either implement modern converting technology in a step-wise manner, converter by converter or are faced with major capital expenditure to replace or upgrade a specific operating unit.

Ausmelt converters may be used on a cyclical basis in precisely the same manner as Peirce-Smith converters and in using the same slag chemistry will provide the added benefit of not requiring retraining of operators in a new metallurgical process.

The synergy of operating a mix of Peirce-Smith and Ausmelt units has not yet been tested at the feasibility study level, but appears to be real.

Issues of processing molten or solid matte in the Ausmelt unit and integration of high strength SO_2 gas into existing gas handling systems will require detail assessment on a case by base basis though on the studies to-date have not presented unduly difficult integration problems.

The foregoing suggests that the Ausmelt Technology converting process has potential as a Peirce-Smith converter replacement and should be incorporated in any technology review by smelter operators.

References

[1] J Schwarz and M R Richardson, "Process Options for Modifying the Outokumpu Refinery Circuit at BSR Ltd to Improve Base and Platinum Group Metal Recoveries", African Mining 1991.