A new process for the thermal refining of zinc: A case study of technology development at Mintek

by A. McKenzie*

Synopsis

During the late 1990s Anglo American PLC was evaluating the Gamsberg zinc deposit in the Northern Cape Province. As the primary South African metallurgical technology provider, Mintek became involved in the evaluation of a pyrometallurgical process for the recovery of zinc from the Gamsberg deposit.

During the 1980s and 1990s Mintek was instrumental in developing DC arc furnace technology for the metallurgical industry. This includes the patented Enviroplas® process for the treatment of zinc bearing waste materials. As a consequence Mintek has developed extensive expertise in the pyrometallurgical processing of zinc bearing materials. However, Mintek's technologies stopped with the production of Prime Western Grade (PWG) zinc. Early on in the evaluation of the Gamsberg project, it became evident that the refining of PWG zinc would play an important part in the economic viability of the project. At the time the only pyrometallurgical technology available for the refining of PWG zinc to Special High Grade (SHG) zinc was the New Jersey process. This process represents 50-year-old technology and has not undergone significant refinement since the technology was developed. In order to provide a complete pyrometallurgical flow sheet for possible implementation at Gamsberg, Mintek assessed the New Jersey process with a view to either improving the technology or developing a new technology appropriate to the 21 century.

In 1998 Mintek convened a consortium consisting of Mintek, the University of Cape Town, Eskom Enterprises, Bateman Metals and Anglo American PLC. The consortium successfully applied to the Innovation Fund for funding to develop a new process for the pyrometallurgical refining of PWG zinc to SHG zinc.

The main aims of the project were to develop a new technology for pyrometallurgical zinc refining that conformed to the following:

- ➤ Decrease the production cost of SHG zinc metal to stimulate the development of the Gamsberg deposit.
- ➤ Be compatible with the current Enviroplas® process, preferably as an add-on to that process.
- ➤ Should use electrical energy to benefit from local price tariffs.

The project commenced at the beginning of 2000 and consisted of three phases:

- ➤ an initial technology search and assessment of the fundamental aspects of zinc distillation.
- ➤ the design of a pilot plant for zinc refining.
- ➤ the manufacture, commissioning and operation of the pilot plant.

A new technology based on a DC arc boiler feeding a packed distillation column was developed and during 2003 the project culminated in the successful operation of a 200 kg/h pilot plant. Ultimately, all of the aims of the project were met and the main outcome is that an advanced process for the pyrometallurgical refining of zinc (the Zincref process) has been developed. The main innovation of the technology was the switch from an energy transfer limited process to a mass transfer limited process (for which a patent has been registered).

Introduction

Starting in the late 1990s Mintek was involved in the development of a new pyrometallurgical process for the refining of Prime Western Grade (PWG) zinc to Special High Grade (SHG) zinc. This paper presents, as a case study, an overview of the methodologies used, progress and the results. The project encompassed all aspects from fundamental research in the laboratory, to the design, construction and operation of a pilot plant to prove the technology.

History

South Africa has the world's fifth largest zinc reserves, but currently produces only about 100 000 tons of zinc metal per year. This just covers local demand for zinc galvanizing, die-casting and zinc precipitation during gold processing. The largest undeveloped South African deposit is the Gamsberg zinc deposit in the Northern Cape Province. This deposit alone is capable of producing 300 000 to 400 000 tons per year of zinc metal but so far could not be cost effectively exploited. During the late 1990s Anglo American PLC was evaluating the feasibility of developing the Gamsberg deposit.

As the primary South African metallurgical technology provider, Mintek became involved in the evaluation of a pyrometallurgical process for the recovery of zinc from the Gamsberg deposit. During the 1980s and 1990s Mintek was instrumental in developing DC arc furnace technology for the metallurgical industry. This includes the patented Enviroplas® process for the treatment of zinc bearing waste materials[1-8]. As a consequence Mintek has developed extensive expertise in the pyrometallurgical processing of zinc bearing materials. However, Mintek's current technologies stop with the production of Prime

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Western Grade (PWG) zinc (after liquation from a conventional ISP lead-splash condenser). Early on in the evaluation of the Gamsberg project, it became evident that the refining of PWG zinc would play an important part in the economic viability of the project. Currently the only pyrometallurgical technology available for the refining of PWG zinc to Special High Grade (SHG) zinc is the New Jersey process. This process is based on 50-years-old technology that has not undergone significant refinement since the technology was developed. In order to provide a complete pyrometallurgical flow sheet for possible implementation at Gamsberg, Mintek assessed the New Jersey process with a view to either improving the technology or developing a new technology appropriate to the 21st century.

In 1998 Mintek convened a consortium consisting of Mintek, the University of Cape Town (to provide input during fundamental research), Eskom Enterprises (the commercialization arm of the electricity supply utility), Bateman Metals (formally Bateman Titaco– a metallurgical engineering and design company) and Anglo American PLC. The consortium successfully applied to the Innovation Fund operated by the National Research Foundation on behalf of the South African Department of Science and Technology (previously DACST), for funding to develop a new process for the pyrometallurgical refining of PWG zinc to SHG zinc, with the specific aim to facilitate the development of the Gamsberg Deposit.

Global primary zinc production is currently split between two processing options:

- electrowinning, based mainly on hydrometallurgical technology
- smelting based on Imperial Smelting Processes (ISP) pyrometallurgical technology and refining based on the New Jersey process.

Variations on the electrowinning technology account for more than 80% of the global production of refined zinc. In general, the electrowinning technology option is considered to be the most cost effective, which explains its high market penetration. Its biggest drawback is that it produces large quantities of leach residues and anode slimes; both of which have a significant environmental impact. This is leading to pressure to decrease the environmental impact of the technology or develop an alternative process that lessens the environmental impact.

The balance of the global zinc metal production is processed pyrometallurgically, using predominantly ISP technology for smelting, combined with New Jersey column refining. This technology predates the electrowinning option and is powered by fossil fuels. The use of fossil fuels creates a niche option in scenarios where electrical power for electrowinning is not available (e.g. the Miasteczko Slaskie plant in Poland). In 1998 there were 13 integrated pyrometallurgical smelting and refining operations worldwide, in addition there were four refineries. The bulk of the flow sheet dates back to the first half of the last century and has only had minor updates since inception. The major drawback of the current pyrometallurgical refining technology is that it is energy inefficient and consequently suffers from a negative environmental stigma.

During the 1950s and 1960s an alternative pyrometallurgical zinc refining process, called the Vacuum De-Zincing (VDZ) process was developed. Two semi-commercial test units were constructed at Avonmouth starting in 1961 and operated at a scale of about one ton per hour of refined zinc. A larger commercial unit was installed during 1967 at Swansea Vale ISF plant (in the UK), it operated at ± 20 000 tons per year until the plant was closed in 1971. The technology, however, proved unable to produce SHG zinc[9]. A number of attempts were made to reassess the technology but none appear to have been followed through.

When evaluating the Gamsberg Deposit, Anglo American had to make the choice between electrowinning and pyrometallurgical technology (the obvious choice was the electrowinning option because they own other electrowinning zinc operations, e.g. Hudson Bay in Canada). However, the Gamsberg ores contain significant quantities of manganese, which the standard electrowinning technology was unable to handle. The ISP based pyrometallurgical technology was also not an option for Gamsberg owing to a lack of a suitable fossil fuel power source. Thus there was no existing technology that could be used at Gamsberg.

Over the past 15 years Mintek has developed and optimized the Enviroplas® process, which in its basic form was intended to recover zinc from waste furnace dusts (primarily electric arc furnace dusts). This technology was suited to reapplication on the Gamsberg ores and extensive pilot plant testing, in conjunction with Anglo American, proved successful at recovering the zinc and overcoming the problems associated with manganese.

This gave Anglo American two process options, viz, modified electrowinning, which has difficulties in handling the manganese in the ores, and the DC arc furnace based Enviroplas® process. One of the drawbacks of the Enviroplas® process was that it only produced PWG zinc, and New Jersey column refining was the only commercial pyrometallurgical zinc refining technology. This was the driving force behind the search for a new pyrometallurgical zinc refining technology, as it was felt that the Enviroplas® process coupled with a new refining technology would address the manganese issues, would be electrically powered, and would be environmentally acceptable.

Thus to summarize, at the start of the project the following existing technology options were available for consideration at Gamsberg:

- Hydrometallurgical based electrowinning technology that had difficulty dealing with the manganese in the ores
- ISP based smelting and New Jersey refining, which are both inefficient and use fossil fuels
- The Enviroplas® technology that lacks a refining option
- VDZ refining that has been piloted but never successfully implemented at a commercial scale.

A viable solution therefore seemed to be to develop a suitable refining option to complement the Enviroplas® process.

The Zincref project

In developing a new refining technology it was decided to go back to basics and start with first principles; the resulting project consisted of the following key activities:

- *Fundamental understanding and bench scale testing*—Modelling of the mass and energy balance considerations in the existing fractional distillation process for the purification of zinc from zinc-lead-cadmium alloys.
- *Theoretical design of an improved reactor for zinc refining*—An assessment of materials that could be used to contain the zinc during refining.
- *Pilot plant development and testing*—Design and construction of a pilot plant to establish the design and operation parameters for a commercial plant.

From the outset the new process was to be based on the following constraints and assumptions:

- The process should primarily support the exploitation of the Gamsberg deposit using pyrometallurgical processing. Thus the process would be based on the best options for a South African 'greenfield' pyrometallurgical zinc refining operation.
- The process should result in a decrease in the production cost of SHG zinc metal to stimulate the development of the Gamsberg deposit.
- The process should be compatible with the current Enviroplas® process, and would be an add-on to that process.
- In the South African context electricity would be the most cost effective source of energy and consequently the process would be based on the use of electrical energy.

The project was broadly divided into three phases:

- phase 1: An initial technology search and assessment of the fundamental aspects of zinc distillation
- phase 2: The design of the pilot plant for zinc refining
- phase 3: The manufacture, commissioning and operation of the pilot plant.

The project began with an assessment of the existing New Jersey process for the thermal refining of zinc. Literature[10]—and techno-economic—studies were undertaken in order to identify possible alternative technologies. Following the commencement of the initial assessment it was realized that without understanding the operation of the current New Jersey process it would be difficult to develop a new process. A study was therefore commissioned which resulted in the generation of a computer model for a New Jersey column. During the modelling process it was realized that a number of parameters required to generate an accurate model would need to be empirically determined, and it is not possible to obtain the required information from an operating plant (largely because it is not possible to take the required samples from an operating column). This led to a laboratory campaign where a small-scale New Jersey column was built. The configuration of this column could be changed in order to assess the effect of column configuration. In addition, using this equipment the liquid and vapour composition for each stage of the distillation could be obtained. It was possible to reconcile the laboratory results with the computer model.

As a result of the preliminary techno-economic assessment, the modelling of the New Jersey column and the laboratory-scale test work on the New Jersey column, it was decided to investigate the use of both a packed distillation column[11-12] and vacuum based distillation. Following an extensive assessment of the issues associated with the vacuum and atmospheric distillation it was decided to proceed with the modified atmospheric process.[*]

It was proposed that the process would consist of:

- a packed distillation column, and
- a transferred plasma heated zinc boiler.

Notwithstanding any disadvantages, a transferred plasma heat source has the following two major advantages:

- High thermal efficiency. Plasma heating should allow efficiencies in excess of 90%. Given that energy costs contribute significantly to the zinc refining costs, an increase in heating efficiency has a significant effect on lowering the processing cost.
- The power density possible with a plasma source is much higher than that possible using other heating systems. As a consequence the boiler unit would be smaller. This means that even for a very large capacity plant only a single boiler unit would be needed.

The preliminary work led to the design and conceptual engineering of a pilot plant that commenced during the third quarter of 2001. The detailed engineering design of the pilot plant was undertaken by consortium partners Bateman Metals (formally Bateman Titaco). The detailed design process commenced at the end of 2001 and the completed detailed engineering design was delivered during October 2002. The detailed engineering designs were reviewed on a regular basis to ensure that the process engineering team and the fabrication team were consulted with respect to design issues and were also fully aware of the design detail. This process resulted in a smooth interaction between the design and fabrication teams.

Overview of pilot plant

The pilot plant was installed in Mintek's Bay 1 pyrometallurgical facility, and the ability to use pre-existing facilities and infrastructure meant that the total cost of the pilot plant was significantly lower than would have been the case for a 'greenfields' installation (by ± 50%). As a consequence there were sufficient funds to build a ± 200 kg/h plant. The pilot plant consists of a DC arc furnace to boil the zinc, connected to a refractory lined packed distillation column for refining the zinc, and finally a surface condenser for condensing the distilled zinc (Figure 1).

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[*] As a result of the work undertaken during Phase 1 it was realized that although the available information indicated that the VDZ process could not produce SHG zinc, there were a number of options that could significantly improve the zinc grade from a vacuum based process. The design of a vacuum based plant proceeded to the conceptual stage and it was established that a vacuum based process offers significant cost advantages over atmospheric distillation. However, the vacuum process was abondoned when it was realized that no materials could be identified that were suitable for the manufacture of a launder for a vacuum based unit. In addition, in order to make use of the heat available from lead streams associated with a zinc refinery (the main economic driving force for the vacuum process) it is necessary to have a heat exchanger to transfer the energy from the lead streams into the PWG zinc stream. There was doubt as to the viability of such a unit based on cost, energy transfer efficiency and materials of construction

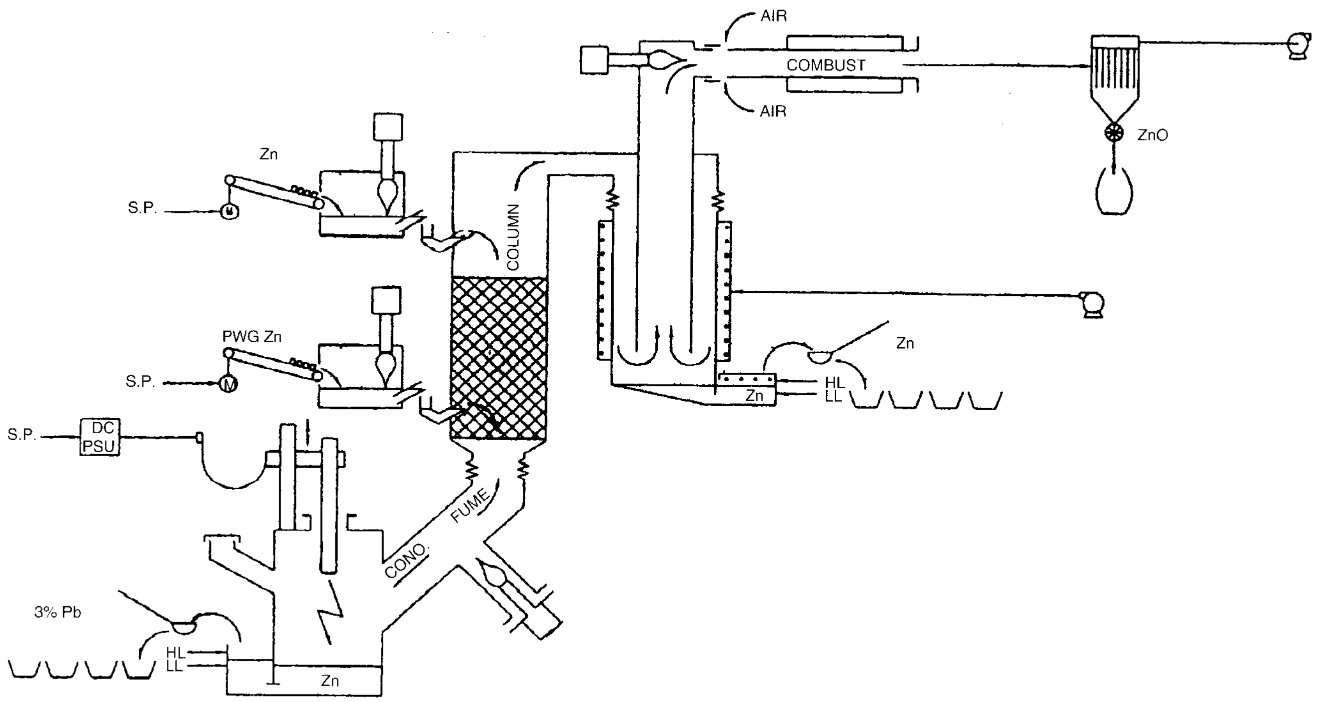

Figure 1—Schematic view of the pilot plant

The main aims of the pilot plant were:

- to verify the new process was capable of refining zinc to less than 30 ppm lead content
- to obtain design parameters for the design of a commercial zinc refinery
- to obtain process performance data for a revised techno-economic evaluation.

In addition to the above main aims, it was intended that operating the pilot plant would:

- assess the performance of the DC arc boiler for zinc
- assess the performance and capacity of the packed column and provide data that could be used for further mass and energy transfer modelling
- assess the design of the condenser
- assess the effect of reflux ratio on the zinc grade.

Following commissioning the plant was run for an extended period during May 2003 to obtain the data required to satisfy the objectives. In total the pilot plant was operated for 562 hours; of this approximately 68 hours were considered steady state operation.

The period of operation was divided into eight sets of operating conditions as per Table I. The operating parameters were varied during the course of the tests to assess the effect of the parameters on the zinc purity (Table I). Product grade was achieved for all conditions tested and there are no clear trends in set point versus grade; this is largely a consequence of the conservative approach adopted in the design. Put another way, the performance envelope was not approached for any of the conditions tested and therefore all the results are similar. This implies that the plant, and particularly the packed column, is capable of far higher capacities than those tested (this will be assessed in additional pilot plant trails).

The data collected for the various conditions allowed for the calculation of the power versus condensation rate curve (Figure 2). During the tests the heat losses from the furnace and column slowly increased as zinc penetrated the inner layers of the refractory (steady state penetration was not achieved during the tests). The data provide a good basis to estimate the power requirements for a commercial plant. The error bars in the graph (+10%, -20%) show the uncertainty with respect to the power requirements (the combined effect of the energy consumption, and feed and product mass uncertainties). The theoretically required power consumption assuming 100% efficiency falls within the uncertainty and as a consequence we are confident that at a commercial scale, thermal efficiencies of 90% and above will be achievable.

Table II shows the calculated reflux ratios based on the heat losses (modelled and measured). Depending on the conditions, the reflux varies from ±30% to 65%. That this variation does not measurably affect the product grade indicates that there is significant scope to further reduce the reflux ratio. Reflux of 20% and below will be tested in additional pilot plant campaigns. In process terms, the lower the reflux ratio the lower the processing costs will be.

In summary, the pilot plant run demonstrated the following:

- The equipment and hence the process was able to produce zinc with a lead content below 30 ppm. Under some of the conditions tested, the lead content was less than 10 ppm.
- The condenser efficiency was greater than 90% (although this was not optimized).
- Zinc boil-up ratios in excess of 80% are possible.
- The total heat losses from the furnace and column were between 90 and 120 kW depending on operating conditions. This is in good agreement with the thermal modelling that indicates expected heat losses of 80 kW from the column alone.
- The heat losses from the column resulted in reflux rates of 35 to 46 kg/h.

Table I

Summary of steady state furnace conditions

Parameter	Condition							
	1	2	3	4A	4B	5A	5B	6
Feed type	PWG	PWG	PWG	PWG	SHG	PWG	PWG	PWG
Feed position	Bottom	Bottom	Bottom	Top	Top	Bottom	Bottom	F.sump
Packing height, m	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.4
Power, kW	100	100	150	150	150	170	150	150
Voltage, V	100	100	100	100	100	100	100	100
Current, A	1000	1000	1500	1500	1500	1700	1500	1500
Steady state duration, h	24	13	7	2.5	4.25	4.5	8.5	4
Condenser product, kg	450	246	593	234	391	319	586	208
Furnace product, kg	255	830	0	75	125	359	411	359
Total product, kg	705	1076	593	309	516	678	997	567
Total feed, kg	1000	1076	593	309	516	678	997	567
Calculated feedrate, kg/h	42	83	85	124	121	151	117	142
Boil-up ratio, %	64	23	100	76	76	47	59	37
Condensate/Furnace	1.76	0.30	-	3.13	3.12	0.89	1.43	0.58
Fuming rate, kg/h	19	19	85	94	92	71	69	52
Average condenser outlet temp, °C	230	210	350	360	400	250	300	230
Pb content of condensate, ppm	22	-	< 5	24	23	-	22	15

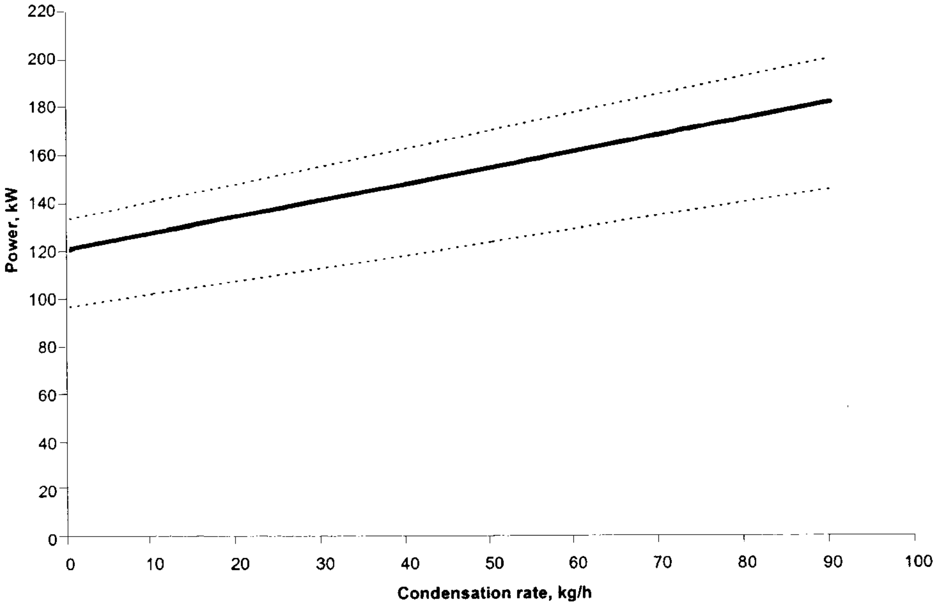

Figure 2—Pilot of power versus condensation rate. Dotted lines indicate the uncertainty

Table II

Calculated reflux ratio based on the assessed heat losses

Condition	Condensation rate, kg/h	Power, kW	Heat losses, kW	Column heat loss, kW	Internal reflux, kg/h	Fuming rate, kg/h	Per cent reflux, %
1	19	100	90	18	35	54	65
2	19	100	90	18	35	54	65
3	85	150	100	20	38	123	31
4	93	150	100	20	38	131	29
5	70	160	120	24	46	116	40

- Additional reflux liquid, up to a maximum of 200 kg/h could be added via the reflux feed system.
- During steady state operation the measured energy requirement to boil one ton of zinc was 0.67 kWh/kg (±20%). This is at most 25% higher than theoretical energy requirement per ton (0.54 kWh/kg) and is considered good for a pilot plant scale operation. It is significantly better than the actual values from commercial New Jersey columns[10].
- A maximum fuming rate of 330 kg/h/m^2 was achieved; at this rate the furnace operation was stable. (The fuming rate could not be increased any further owing to limitations on the feed rate.)
- Under steady state conditions the operational parameters were as follows:

- Column inlet pressure	1.1 to 1.8 kPa
- Furnace refractory temperature	800°C
- Column outlet refractory temperature	850°C
- Condenser gas outlet temperature	300°C
- Net operating power	100 to 170 kW
- Operating voltage	100 V
- Operating current	1 to 1.7 kA

Techno-economic evaluation

A first pass techno-economic assessment of the process was made; one of the main uncertainties in such an assessment is the assumptions that need to be made during the process modelling. This can lead to significant uncertainty in the financial figures. One method of minimizing the uncertainties is to undertake the techno-economic modelling on a comparative basis, where a new process is compared with an existing process. In this way, many of the assumptions that are required are common to both the new and existing technology, and they effectively cancel out. The result is that whilst there may be errors in the absolute value of the techno-economic results, on a relative basis the cost of a new technology can be compared with an existing one.

When a pyrometallurgical process option was initially recommended to Anglo American, a techno-economic assessment was conducted for a New Jersey refinery. These figures have been reassessed and used as a comparison for the Zincref technology.

Capital costs

The capital cost comparison for the 300 000 ton per year New Jersey refinery and the Zincref refinery is given in Table III. It should be noted that in the current configuration, the Zincref technology still uses New Jersey columns for the removal of cadmium from the zinc. Based on the comparison it is clear that at the 300 000 ton per year (Gamsberg) scale, there is a significant capital cost saving using the Zincref technology. This calculation is sensitive to the scale of the operation, and at the 50 000 ton per year scale (Figure 3), the capital cost differential has decreased to approximately 5 per cent.

Variable costs

The variable cost comparison for the 300 000 ton per year New Jersey refinery and a Zincref refinery is given in Table IV. It should be noted that once again the cost for the Zincref technology is meaningfully lower than the New Jersey technology. The differential is not as great as was the case for the capital costs, and this is largely a consequence of the limited scope to lower the energy requirements for boiling the zinc.

Fixed costs

The fixed cost comparison for the 300 000 ton per year New Jersey refinery and a Zincref refinery is given in Table V. The fixed costs for the Zincref refinery are substantially lower than those for the New Jersey refinery. This is largely a consequence of the lower capital costs and a much lower labour component. The significant decrease in the labour complement is a result of a single Zincref column as opposed to a total of 33 columns for the New Jersey refinery. This clearly leads to a reduction in staff required to service the plant.

Table III

Capital cost comparison for 300 000 tonne per year New Jersey refinery and a Zincref refinery. Figures are in million rand

Description	New Jersey Refinery	Zincref Refinery
Earth works and civils	R35	R35
Building and cranes	R39	R39
New Jersey Plant	R329	R76
Furnace (30 MW)		R47
Furnace refractories		R24
Furnace feed/fractionation		R20
Utilities/ancillaries	R7	R8
Electrical		R50
Instrumentation		R8
Royalty		R7
Total	R410	R314
Rand cost per ton zinc over 10 years	R137	R105

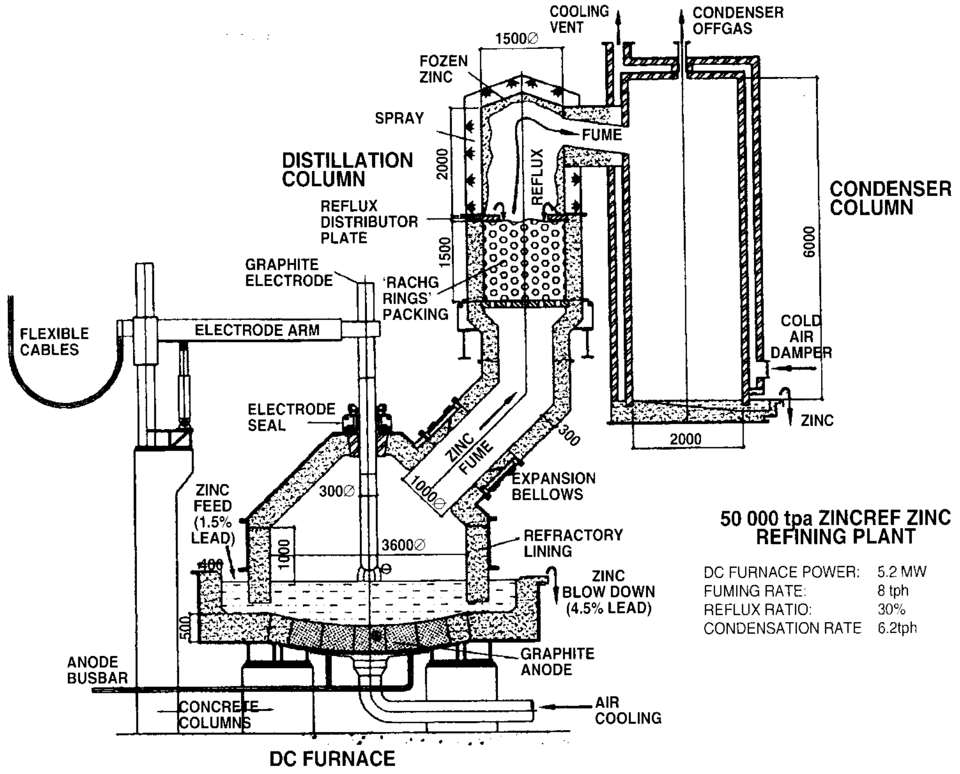

Figure 3—Schematic of a 50 000 tpa Zincref unit

Table IV

Variable production cost comparison for 300 000 ton per year New Jersey refinery and for a Zincref refinery

Description	Unit	Unit cost	New Jersey Refinery		Zincref Refinery	
			Units/t Zn	Cost/t Zn	Units/t Zn	Cost/t Zn
Electrodes	kg	R18.00			2	R36.00
Electricity	MWh	R150.00	0.08	R12.00	0.9	R135.00
Fuel oil	L	R2.00	134	R268.00	30.82	R62.00
Consumables		R25.00	0.5	R13.00	1	R25.00
Total				R293.00		R258.00

Table V

Fixed production cost comparison for 300 000 ton per year New Jersey refinery and for a Zincref refinery

Description	New Jersey Refinery		Zincref Refinery	
	Units	Cost/t Zn	Units	Cost/t Zn
Labour		R42.05		R23.38
Superintendent	1		1	
Foreman	12		4	
Senior Operator	18		8	
Operator	30		32	
Labourer	75		16	
Maintenance (4% of Capex)	R16 410 000	R54.70	R12 500 000	R41.67
Insurance (0.75% of Capex)	R3 077 000	R10.25	R2 344 000	R7.81
Total		R107.00		R72.86

Table VI

Overall cost comparison for a 300 000 ton per year refinery using New Jersey refinery and a Zincref refinery

	New Jersey Refinery	Zincref Refinery	Difference
Capex	R137	R105	- 23%
Variable Opex	R293	R258	- 12%
Fixed Opex	R107	R73	-32%
Total	R537	R436	-19%

Total costs

The overall cost comparison at the 300 000 ton per year scale is given in Table VI. The results of the techno-economic modelling show that in South Africa, a Zincref refinery has the potential to be almost 20% cheaper than a New Jersey refinery in refining zinc. In absolute terms the savings are roughly equally distributed between the three cost components. The overall cost analysis is sensitive to the scale of the refinery, and the gap increases in favour of the Zincref Technology as the scale increases. However, even at the 50 000 tons per year scale the Zincref Technology still offers a cost benefit over the New Jersey Technology.

Summary

The main objective of the project was to develop a new pyrometallurgical zinc refining technology that was compatible with the Mintek Enviroplas® process and that could be implemented at the Gamsberg Deposit.

It is clear that the project was successful in developing a suitable technology and demonstrating it on a pilot plant scale. In this respect the objectives of the project have been satisfied and a new technology for the pyrometallurgical refining of zinc has been developed— the so-called Zincref technology. The main features and benefits of the Zincref technology are as follows:

- The process is mass transfer limited and consequently the equipment size is minimized.
- There is almost no limitation on the scale of the DC boiler and packed column, and therefore for large operations multiple units are not required.
- The process is electrically powered.
- The process produces almost no environmental residues or wastes. The lead-rich stream from the boiler is recirculated for liquation and then back to the lead-splash condenser.
- The technology is compatible with, and complements existing pyrometallurgical technology for the treatment of zinc feedstocks.
- In a South African context, a Zincref refinery of 300 000 tons per year will produce SHG zinc at up to 20% less than the current New Jersey technology.
- The process is very flexible and produces SHG zinc from a wide variety of operating conditions.

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References

1. SCHOUKENS, A.F.S., NELSON, L.R., and BARCZA, N.A. Plasma-arc treatment of steel-plant dust and zinc-containing slag-theoretical and practical considerations. *Recycling of Lead and Zinc the Challenge of the 1990s, Proceedings of an international conference organised by the International Lead and Zinc Study Group Sub-Committee on Recycling*, Rome, June 1991, pp. 361–370.
2. SCHOUKENS, A.F.S., SHAW, F., and CHEMALY, E.C. The Enviroplas process for the treatment of steel-plant dusts. *Journal of the South African Institute of Mining and Metallurgy*, vol. 93, no. 1, January 1993, pp. 1–7.
3. Barcza, N.A., Hutton, C.J., Freeman, M.J., and Shaw, F. The treatment of metallurgical wastes using the Enviroplas process. *International symposium on Extraction and Processing for the Treatment and Minimisation of Wastes*, 1994 TMS Annual Meeting, 27 February—3 March 1994, San Francisco. Publication of the Minerals, Metals and Materials Society, Warrendale, Pennsylvania, 1993, pp. 941–962.
4. BARCZA, N.A., ROBERTSON, D.G.C., SCHOUKENS, A.F.S., SHAW, F., DENTON, G.M., WORCESTER, A.W., and BAILEY, D.J. Enviroplas technology for the recovery of lead and zinc from lead blast furnace slag. Presented at *Recycling lead and zinc into the 21st Century: 6th International Conference of the International Lead and Zinc Study Group*', Madrid, Spain, 23–28 June, 1995.
5. SCHOUKENS, A.F.S., DENTON, G.M., and JONES, R.T. Pilot-plant production of Prime Western grade zinc from lead blast-furnace slags using the Enviroplas process. *Proceedings of the third international symposium on recycling of metals and engineered materials*, Point Clear, Alabama, 12–15 November 1995. Publication of the Minerals, Metals and Materials Society, 1995, pp. 857–868.
6. ABDEL-LATIF, M.A. Fundamentals of Zinc recovery from metallurgical wastes in the Enviroplas process. *Minerals Engineering*, vol. 15, no. 11, Supplement S, 2002, pp. 945–952.
7. ASSIS, G. Emerging pyrometallurgical process for zinc and lead recovery from zinc-bearing waste materials. *37th Zinc and Lead Processing Symposium*. 1998 CIM Meeting, 16–19 August 1998, Calgary, Canada. pp. 243–265.
8. SCHOUKENS, A.F.S., ABDEL-LATIF, M.A., FREEMAN, M.J., and BARCZA, N.A. The Enviroplas process for the recovery of zinc, chromium and nickel from steel-plant dust, *1996 Electric Furnace Conference Proceedings*, pp 341–351.
9. LEE, R. Capital and Operating Costs for Zinc Refineries to produce 200 000 and 50 000 T/Y of SHG Zinc. Imperial Smelting Processes Report 2765. 2000.
10. REDDY, D. Summary of Literature Study performed on the Refining of Zinc metal 2000.
11. GLOVER, G. The modelling and simulation of a packed distillation column for use in lead-zinc refining. Part 1: Model Development. Mintek Technical Memorandum No. 14696, 2001.
12. GLOVER, G. The modelling and simulation of a packed distillation column for use in lead-zinc refining. Part 2: Mass Transfer Efficiency. Mintek Technical Memorandum No. 14698, 2001.
13. GARZ, R. Optimised heating system for an improved zinc refining process. Electrotek, Resource and Strategy Research Division Research Report No. RES/RE/00/10353. 2001. ◆