

Energy consumptions for Kell hydrometallurgical refining versus conventional pyrometallurgical smelting and refining of PGM concentrates

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Current practice for the recovery of platinum group metals (PGM) from flotation concentrates is by energy-intensive smelting processes followed by separation and refining of the base and precious metals. Energy costs are rapidly increasing in South Africa and this trend is forecast to continue in future years. Moreover, the smelting operations are highly susceptible to deleterious constituents, particularly chromite; and the increasing tonnages of UG2 chromititic ore being mined results in an increasing chromite content of smelter feeds. Hence there is a substantial incentive to assess and implement alternative processes to smelting for the treatment of PGM concentrates. The Kell process is a patented hydrometallurgical alternative to smelting that is totally insensitive to the chromite content of the feed concentrate and comprises three commercially proven unit operations (pressure oxidation leaching of base metals and sulphur, roasting and chlorination of precious metals).

The Kell process provides the opportunity for existing and new PGM producers to significantly reduce their energy consumption, and in particular their consumption of electricity, by removing the need to smelt PGM concentrates. Energy costs, greenhouse gas emissions and installed power requirements are also much reduced. Compared with smelting and refining, these reductions are calculated as:

- Total energy consumption—50% reduction
- Electrical energy consumption—84% reduction
- Energy consumption costs—76% reduction
- CO₂ emissions—70% reduction
- Installed power requirement—92% reduction.

The data obtained from simple laboratory batch amenability testing can be readily applied to the Simulus mass and energy balance simulation procedure to determine energy and reagent consumptions, equipment selection and process optimization.

The applicability of Kell to treating low-grade 'dirty' concentrates with high UG2 content as well as to polymetallic concentrates containing base metals as the major payable metals with subordinate PGM means that these savings can also be expected when the process is used for treating a range of concentrate types and grades.

Introduction

Recovery of platinum group metals (PGM) from flotation concentrates is currently achieved by energy-intensive smelting processes that are highly susceptible to deleterious constituents, such as chromite, in the feed concentrate. Given the current rapid increase in energy costs over the recent past and forecast in future years, as well as the increasing chromite content of smelter feeds due to the higher proportion of UG2 chromititic PGM ore (UG2) being mined, there is a large incentive to assess alternative processes to smelting for the treatment of PGM concentrates.

The Kell Process

The Kell process is a hydrometallurgical alternative to smelting of concentrates containing PGM and base metals (BM). It was specifically designed for UG2 concentrates^{1,2} and is totally insensitive to the chromite content of the feed concentrate. The patented process^{3,4,5} comprises three basic sequential unit operations, all of which are well proven and commonly utilized in the metallurgical industry (Figure 1) and provide high recoveries of base metals and precious metals.

The three unit operations are:

Stage 1

Aqueous pressure oxidation in an acidic sulphate medium to dissolve the sulphides and remove the base metals while minimizing dissolution of the precious metals. The conditions used are standard for base metal dissolution, with rapid leach kinetics giving an autoclave residence time of approximately 30 minutes.

Stage 2

Roasting of the pressure oxidation residue to condition the PGM mineral phases, rendering them amenable for subsequent leaching. Since the sulphides have been removed in the pressure oxidation stage, the roaster off-gases contain minimal SO_2 , eliminating the need for an expensive acid plant.

Stage 3

Atmospheric leaching of the precious metals in chloride media in the same manner as typically used in PGM refineries to prepare the PGM for separation and refining.

The dissolved metal streams for the base metals and precious metals are each further processed to recover the payable metals by existing refining technologies practised by the PGM and BM industries—the exact processes and products being site specific and dependent on the user. The solids waste streams are impounded in a tailing storage facility, solution streams are recycled with any bleed streams being neutralized, and gaseous emissions are scrubbed before release, thus minimizing environmental impacts from the solid, liquid and gaseous phases.

A key feature of Kell is that the leaching of the base metals and precious metals is kept entirely separate, with no mixing of the sulphate and chloride process streams. This allows process conditions and materials of construction to be optimized for each metal suite, reduces reagent and water consumption, and provides flexibility in plant design and operation.

Smelting

The PGM smelting facilities in South Africa have been summarized by Jones⁶ and the smelters treat blends of Merensky, UG2 and Platreef concentrates. The 'nameplate' installed power of Anglo Platinum Limited's smelters is 185 MW⁷. Smelting of PGM concentrates in South Africa began with Merensky concentrates and over time increasing amounts of UG2 concentrates have been treated as the proportion of UG2 ore mined by the industry increases. Some Platreef concentrates are also processed by Anglo Platinum at the Polokwane smelter^{8,9}. Smelting of PGM concentrates in South Africa is typically by production of a furnace matte and silicate slag in a rectangular six-electrode or circular three-electrode alternating-current resistance furnace, with the circular furnaces used for UG2-predominant concentrates⁶. The furnace matte, or 'green matte', has iron and sulphur reduced by oxidation in a converter to produce a 'white matte' which is then further processed to recover the base and precious metals. Merensky and Platreef concentrates have similar smelting characteristics (higher sulphides and base metals and lower chromite), whereas UG2 concentrates have low sulphide and base-metal contents and higher chromite content. Smelting of UG2 concentrate requires blending with Merensky or Platreef, and, as the proportion of UG2 increases, higher temperatures and power densities are required to keep the chromite in solution in the slag. Furnaces are operated on a limiting factor of tonnes of chromite held up in the furnace so that chromite solubility within the melt is maintained, and this results in a limiting UG2 concentrate throughput for each furnace and hence for the industry. Smelter feed management requires the UG2 flotation concentrators to be operated with constraining limits on the concentrate with respect to chromite grade and contained chromite mass, and these limits reduce the overall PGM recovery from the concentrators. Where smelters purchase or toll treat UG2 concentrate from third parties, the contracts contain provisions for penalties for

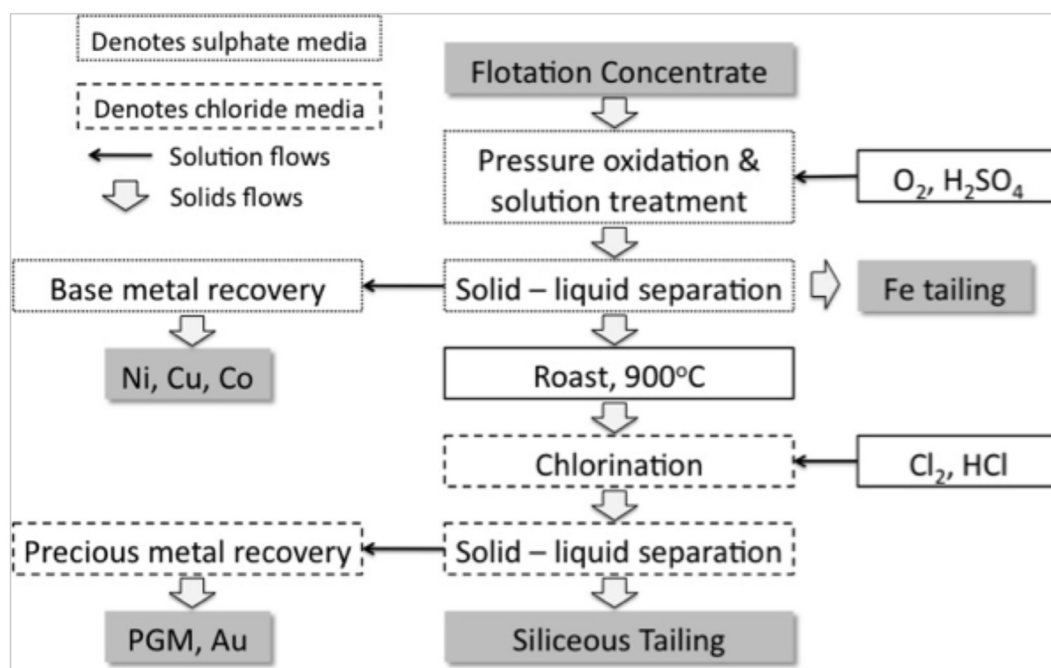


Figure 1. Simplified block flow diagram of the Kell process

excess chromite content and have an upper chromite limit whereby concentrate batches can be rejected¹⁰.

Kell process simulation and energy calculations

For the purpose of determining the energy requirements, the Kell process has been simulated treating an 80:20 blend of typical UG2 and Merensky concentrates as described in Tables I and II. This blend and a throughput of 25 t/h (nominally 200 000 t/y) were selected to match those of a currently operating 28 MW circular furnace that treats the highest proportion of UG2 of all installed furnaces¹¹. The process output streams of the Kell simulation are:

- Nickel and copper as metallic cathode by electrowinning
- Chloride pregnant solution containing the precious metals for separation purification
- Filtered solids waste containing the silicates, iron and aluminium
- Waste solution streams
- Scrubbed off-gases

The simulation model is a mass and energy balance considering all major unit operations at steady state. All significant process streams are included and balanced, as per a typical process flow diagram. The model was constructed using the IDEAS simulation software, supplied by Andritz Automation.

Table I
Elemental composition of concentrate used for Kell simulation

Precious metals, g/t		Base metals, %		Other, %	
Pt	185	Ni	2.50	O	38.3
Pd	78	Cu	1.50	S	4.40
Rh	32	Co	0.10	H	0.04
Ru	43	Fe	15.2	F	0.13
Ir	2	Al	1.91	As	0.001
Os	5	Mg	11.4	Te	0.001
Au	5	Si	21.4	Bi	0.006
3PGM+Au	300	Ca	1.0		
6PGM+Au	350	K	0.34		
		Cr	1.50		
		Zn	0.05		
		Na	0.03		

The feed concentrate is defined as a comprehensive mineral suite, as given in Tables I and II, including all the chemical and thermodynamic property data. Detailed chemical reactions are modelled to yield the specified input reaction extents, based on both test data and industrial practice. A rigorous energy balance is performed over each unit operation, giving an accurate estimate of water, steam, fuel and electricity consumption throughout.

The model output gives stream-by-stream compositions, including all relevant elements such as the platinum group metals. Reagent consumptions and overall recoveries are also output.

The Kell simulation model has been developed by Simulus as an important part of the ongoing process development for specific applications, with the flexibility to model the response of concentrates using data derived from simple laboratory batch testing of 5 kg of sample. Once a concentrate is characterized various circuit configurations and process conditions can easily be modelled to optimize capital and operating costs, in particular with regard to site-specific requirements.

Comparison of energy consumptions

For this study specific energy consumptions per tonne of concentrate are determined so that they can be directly compared, and furthermore can be applied to other operations having different throughputs. The energy consumptions and other data for existing smelting and refining operations has been sourced and derived from literature and public reports^{8,9,11,12}.

Smelting concentrate and refining smelter matte

The net specific energy consumptions for melting UG2 and Merensky concentrates in the Polokwane smelter have been given by Van Manen⁸ as 667 kWh/t and 554 kWh/t respectively, calculated from the concentrate mineralogies, relevant mineral enthalpies and furnace conditions. From these values an 80:20 UG2:Merensky blend thus has a net melting energy consumption of 644 kWh/t. The Polokwane smelter is one of the most recently installed and has been designed to accommodate a higher UG2 content than other rectangular furnaces, with design Cr₂O₃ content in the feed of 4%; it has a design throughput of 650 000 tonnes per

Table II
Mineralogical composition (in mass %) of concentrate used for Kell simulation

PGM minerals		Sulphides		Gangue minerals	
Cooperite PtS	0.0137	Chalcopyrite CuFeS ₂	4.33	Enstatite, orthopyroxene Mg ₂ Si ₂ O ₆	41.3
Vysotskite PdS	0.0094	Pentlandite NiFeS	6.57	Ferrosilite, orthopyroxene FeSiO ₃	23.0
Laurite RuS ₂	0.0070	Millerite NiS	0.39	Plagioclase, tectosilicate CaO.Al ₂ O ₃ .2SiO ₂	6.84
Sperrylite PtAs ₂	0.0023	Cattierite CoS ₂	0.21	Albite, tectosilicate NaAlSi ₃ O ₈	3.42
Moncheite Pt,PdTe,Bi	0.0014	Pyrrhotite Fe _{0.9} S	0.52	Talc, chlorite 3MgO.4SiO ₂ .H ₂ O	5.68
Kotulskite PdTe,BiS	0.0013	Pyrite FeS ₂	0.36	Chromite FeCr ₂ O ₄	3.23
Ferroplatinum Pt ₃ Fe	0.0056	Sphalerite ZnS	0.07	Annite, biotite mica KFe ₃ AlSi ₃ O ₁₁ .5H _{1.5} F _{0.5}	2.01
				Phlogopite KMg ₃ AlSi ₃ O ₁₀ F(OH)	2.01

Table III
Total, Smelting and Refining energy consumption for Anglo Platinum Ltd in 2009¹²

Item	Total energy 2009 ^a PJ	Smelting specific energy consumption ^b			Refining specific energy consumption ^b			Smelting + refining specific energy consumption ^b		
		GJ/t	kWh/t	%	GJ/t	kWh/t	%	GJ/t	kWh/t	%
Electricity	18.55	3.23	897	71.3	0.60	167	34.0	3.83	1,064	60.8
Coal	3.37	1.14	317	25.2	1.14	335	64.1	2.28	633	36.2
Liquid fuels	1.56	0.01	4	0.3	0.03	9	1.9	0.05	13	0.8
Gas	0.22	0.14	39	3.10	-	-	-	0.14	39	2.3
Total	23.70	4.53	1 258	100.0	1.77	492	100.0	6.30	1 749	100.0

- a. Total for mining, concentrating, smelting and refining
b. Per tonne of concentrate to smelters at design throughput of 1 480 000 t/y⁹

Table IV
Specific energy consumptions for the Kell Process and the smelting and refining operations of Anglo Platinum Ltd¹²

	Kell process (incl. BMR and PMR) ^a			Anglo Platinum 2009 Smelting + Refining ^b		
	GJ/t	kWh/t	%	GJ/t	kWh/t	%
Electricity	0.65	180	21	3.83	1 064	61
Coal	2.45	680	78	2.28	633	36
Gas + Liquid Fuels	0.03	9	1	0.19	53	3
Total	3.13	869	100	6.30	1 749	100

- a. Per tonne of concentrate at throughput of 200 000 t/y
b. Per tonne of concentrate to smelters at design throughput of 1 480 000 t/y⁹

year at 85% availability (87 t/h); and furnace energy consumption of 766 kWh/t⁹. Furnace energy losses are designed at 10 MWh/h⁸ which at design throughput is 115 kW/t, giving a gross furnace energy consumption for an 80:20 UG2:Merensky concentrate of 759 kWh/t.

The energy consumption for the smelting and refining operations of Anglo Platinum Ltd ('APL') in 2009 is presented in Table III¹², and amount to 28% and 11% respectively of all energy consumption, with mining and concentrating comprising the remainder. The total electrical energy consumption for APL smelting operations is calculated as 897 kWh/t, the difference between this and the furnace electrical energy consumption being the power associated with slag cleaning, drives, fans and ancillary equipment. Energy derived from coal for drying of the concentrate and gas for green matte converting comprises the majority of the remaining energy consumption in the smelting operations.

Refining operations vary in detail from producer to producer; at APL they begin with milling slow-cooled crushed converter matte and magnetic separation to produce two fractions that pass to the base metal refinery (BM⁷) and the PGM refinery (PMR). The BMR consists of pressure oxidation, solvent extraction and electrowinning for production of nickel and copper metal cathodes and cobalt is produced by precipitation of cobalt sulphate. In the PMR the PGM fraction from the matte is leached with hydrochloric acid in the presence of chlorine gas and the individual metals are sequentially separated from the leach solution and refined to final products. In the refining process coal is the major energy input (64%) for production of steam to heat process solutions and electricity is predominantly used for electrowinning of the nickel and copper. Total energy consumption at APL for smelting and refining thus equates to 6.3 GJ/t concentrate (1 749 kWh/t), with 61% derived from electricity and 36% from coal.

Kell process

There are three main energy consumption areas in the Kell process:

- Roasting consumes fuel, such as coal or gas, with coal being used in this simulation.
- Various stages in the hydrometallurgical circuits consume energy in the form of steam for heating of the process slurry and solution streams.
- Electrical energy is consumed by electrowinning of base metals, drives of rotating equipment such as pumps, agitators, fans and blowers and other ancillary equipment. In this study, the sizes of major drives have been estimated and the installed power and consumed energy increased by a further 30% to allow for minor drives. In addition, an allowance has been made for drives in the PMR.

The energy consumption and energy types for the various Kell unit operations are given in Table IV. Roasting consumes 2.45 GJ/t of feed concentrate. However, most of this energy is recovered in the roaster off-gases by generation of steam for use throughout the hydrometallurgical areas. In fact, the roaster waste-heat boiler produces more steam than is required in the pressure oxidation, residue leach, iron removal and chlorination leach stages combined and this excess of 0.54 GJ/t is available for use in the PMR if located on the same site.

Electrowinning of the base metals requires around 95 kWh/t of concentrate and electric drives 85 kWh/t. An allowance for use of gas and liquid fuels amounting to 1% of the total is included. The Kell process consumes a total of 3.13 GJ/t (869 kWh/t). This energy consumption equates to about half of that reported for conventional smelting and refining operations, representing a significant potential upside in energy savings. Should a Kell plant be located next to an existing smelter to expand production, there are substantial opportunities to further improve the energy

efficiency of the Kell process through the utilization of smelter furnace waste heat to preheat the leach feed streams and roaster feed streams, thereby reducing the overall energy requirements.

Greenhouse gas emissions

The main greenhouse gas (GHG) emission from smelting/refining and Kell is CO₂ arising directly from on-site combustion of coal and fuels and indirectly from the use of electricity. A comparison derived from the energy consumption analysis (Table V) shows that conventional smelting and refining produces 1 455 kg CO₂ per tonne of concentrate compared with 433 kg CO₂/t for Kell, with almost all of the difference arising from the lower electricity consumption by Kell. Hence, users of the Kell process can mitigate their GHG emissions and future carbon costs.

Energy Costs

The cost of energy consumption per tonne of concentrate is given in Table VI for Kell and for smelting and refining and is calculated as R140/t and R580/t, respectively. Similarly as for CO₂ emissions, most of the difference is accounted for by the lower electricity consumption of Kell. The electricity price in South Africa is set to increase by 25% per annum in 2011 and 2012¹⁴, thereby markedly increasing this differential in the future, giving further impetus toward incorporation of processes that have lower electricity consumption.

Table V
Greenhouse gas emissions for the Kell process and derived for smelting and refining operations of Anglo Platinum Ltd¹²

	Kell process (incl. BMR and PMR) ^a		Anglo Platinum 2009 smelting + refining ^b	
	kg CO ₂ /t	%	kg CO ₂ /t	%
Electricity ^c	186	43	1 096	75
Coal ^d	222	51	207	14
Gas + Liquid Fuels ^e	25	6	152	11
Total	433	100	1 455	100

- a. Per tonne of concentrate at throughput of 200 000 t/y
 b. Per tonne of concentrate to smelters at design throughput of 1 480 000 t/y⁹
 c. Eskom emission of 1.03 kg CO₂/kWh¹³
 d. Coal emission of 2.24 kg CO₂/kg coal
 e. Energy content 0.026 GJ/L and emission of 2.9 kg CO₂/L

Capital requirements for power installation

With Eskom having limited capacity to provide power for new installations in the medium term, the opportunity to install energy-intensive processes such as smelting to increase capacity at existing operations or at greenfields projects becomes limited. The low electrical energy requirement of the Kell process results in an installed power requirement (including BMR and PMR) of approximately 3 MW for 200 000 t/y concentrate capacity, or 15 W per annual tonne capacity. This compares with smelting and refining requiring approximately 180 W per annual tonne, being 36 MW installed power requirement for 200 000 t/y. This reduction in installed power leads to lower capital cost for electrical supply infrastructure, which is now charged by Eskom to the user as an up-front cost rather than being amortized over future accounts. As an alternative to new smelter installations, Kell also has the potential to remove the electricity supply as the critical path item, or to mitigate a severe project delay arising from an inability for Eskom to supply the required electrical energy.

Conclusion

Essentially, the Kell process replaces a smelting furnace with a roaster treating a non-sulphidic feed. By removing the need to smelt PGM concentrates the Kell process provides the opportunity for existing and new PGM producers to significantly reduce their energy consumption and in particular their consumption of electricity. Energy costs, greenhouse gas emissions and installed power requirements are also much reduced. Compared with smelting and refining, these reductions are calculated for Kell for this comparison with smelting as:

- Total energy consumption—50% reduction
- Electrical energy consumption—84% reduction
- Energy consumption costs—76% reduction
- CO₂ emissions—70% reduction
- Installed power requirement—92% reduction.

The data obtained from simple laboratory batch amenability testing can be readily applied to the Stimulus mass and energy balance simulation procedure to determine energy and reagent consumptions, equipment selection and process optimization.

The Kell process is insensitive to chromium content in the feed and to feed grades, hence raising the potential application to treating low-grade 'dirty' concentrates with high UG2 content that cannot be smelted in existing furnaces. The applicability of Kell to polymetallic

Table VI
Specific energy cost for the Kell process and the smelting and refining operations of Anglo Platinum Ltd¹²

	Kell process (incl. BMR and PMR) ^a			Anglo Platinum 2009 smelting + refining ^b		
	Cons./t	Cost R/t	%	Cons./t	Cost R/t	%
Electricity, kWh	180	87 ^c	62	1,064	511 ^c	88
Coal, t	0.10	50 ^d	35	0.09	46 ^d	8
Gas + liquid fuels, L	1.18	4 ^e	3	7.28	23 ^e	4
Total		140	100		580	100

- a. Per tonne of concentrate at throughput of 200 000 t/y
 b. Per tonne of concentrate to smelters at design throughput of 1 480 000 t/y⁹
 c. Electricity cost R0.48/kWh
 d. Coal energy content 25 GJ/t and cost R500/t
 e. Energy content 0.026 GJ/L and GHG cost R3.14/L
 Cons. - Consumption

concentrates containing base metals as the major payable metals with subordinate PGM means that these savings can also be expected when the process is used for polymetallic concentrates. This range of applicability to diverse concentrate types, along with the environmental benefits and the insensitivity to impurities suggests that the Kell process potentially allows for a step-change in overall flotation practices that can lead to higher overall metal recoveries.

By installing the Kell process new entrants to the PGM industry can have the ability to produce their own metals on site, negating the need to sell concentrate to the existing smelters. This can provide strategic and economic benefits as well as gaining beneficiation credits in terms of current legislation.

Existing producers can install Kell adjacent to either their smelting or refining facilities, or at mine sites, to enable production to be increased without having to significantly increase installed power. The concentrate feed balance to the smelters can be changed to better optimize the overall energy efficiency and metal recoveries.

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Keith Liddell has extensive experience in the financing, development and operation of resource projects. He has worked in the platinum industry, starting at Mintek as Group Leader – Precious Metals from 1981 to 1988, with a focus on PGMs and refractory gold, and received two silver medals for his contribution to the development of platinum concentrators. Mr. Liddell is the former Managing Director of Aquarius Platinum Limited, and is currently deputy Chairman of Platmin Ltd. Mr. Liddell is a registered Professional Engineer in Australia, South Africa and the United Kingdom and holds a number of patents relating to platinum processing and ultra-fine milling.

Tim Newton and Brett Muller are directors of Stimulus, an engineering firm offering technical services to the minerals industry. Stimulus has provided flowsheet simulations, engineering studies and detailed design to over 70 projects around the world. Stimulus undertook the mass and energy balance in support of the Kell process design.