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Process routes for beneficiation of noble metals from Merensky and UG-2 ores

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SYNOPSIS

The Merensky and UG-2 Reefs are in close proximity to each other, but there are differences in their gangue mineralization and the grain size of the noble metals and sulphides they contain.

These differences and their effect on the behaviour of Merensky and UG-2 ores during treatment are examined. It is shown that, although the same basic processing route is used for both ores, the operating conditions for the unit operations differ. Although the overall recovery for UG-2 ore is lower than that for Merensky ore at present, there is a potential for improvement. This lies in the preconcentration stage, particularly in the treatment of the coarse fraction of the flotation tailing.

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LAURENCE BRUCE McRAE was born in Johannesburg and matriculated from the Jeppe High School, Johannesburg, in 1953. He gained practical experience as a technician while working in industry and at the University of the Witwatersrand. After being awarded a bursary by Gold Fields of South Africa Limited, he went on to study metallurgy, and graduated from the University of the Witwatersrand in 1964. As a postgraduate student at that University, he lectured in metallurgy until he was awarded the M.Sc.(Eng.) degree. He was appointed as a senior scientist at Mintek in 1969 and was seconded to Mintek's Pyrometallurgy Research Group at the University of the Witwatersrand. Mr McRae is now a chief engineer in the Pyrometallurgy Division at Mintek.

INTRODUCTION

As a World producer of the platinum-group metals (PGM), South Africa ranks second only to the U.S.S.R. It is the only country in which the noble metals (the PGM plus gold) are of primary economic importance in the exploitation of the orebody. Also it is the only country in which large reserves are present. Elsewhere the noble metals are recovered as valuable byproducts, mainly of nickel production. Therefore South African producers have the advantage that they can vary their production to suit prevailing market requirements.

Most of the PGM are contained in the Merensky and UG-2 Reefs of the Bushveld Complex, and three mining groups are currently involved in the exploitation of these reefs. They are: Johannesburg Consolidated Investment Co. Ltd (JCI) who own Rustenburg Platinum Mines (RPM), the largest producer, Gencor who own Impala Platinum Ltd, and Lonrho and Falconbridge who jointly own Western Platinum Limited, the smallest producer. Each group has its own infrastructure of concentrators, smelters, and base-metal and noble-metal refineries.

The Merensky Reef has been mined since the late 1920s, but the UG-2 Reef has been exploited in its own right only since early 1983. However, some producers have mixed UG-2 and Merensky ores and treated them together. The Reefs are close to each other and both of them contain economic amounts of the noble metals, but they differ in certain respects, and this affects the method of preconcentration and smelting used.

RESERVES AND VALUE

The Merensky and UG-2 orebodies occur in the layered mafic rock in the Critical Zone of the Bushveld Complex, which is a large magmatic intrusion situated in the central Transvaal. Together with the unexploited Plat Reef, the Merensky and UG-2 Reefs contain about 80 per cent of the World's reserves of the noble metals. Of major importance in the mining of these ores is the fact that they lie uniformly over great distances and that large tonnages occur at shallow depths. The locations of the noble-metal mines are shown in Fig. 1, from which it can be seen that the majority are situated on the western lobe of the Bushveld Complex[1].

The reserves of Merensky and UG-2 ores to a depth of 1200 m have been estimated[2] to be 3300 Mt and 5420 Mt respectively. The noble-metal content of Merensky ore varies from 3 to 11 g/t (in the region of the upper chromite stringer)[3], and that of UG-2 ore from 4 to 10 g/t.[4] Average grades of the individual noble metals in the ore are shown in Table 1, together with estimates of the value of the ores *in situ*.

On the basis of noble-metal contents shown in Table 1, the value of the UG-2 Reef is $13 per tonne greater than that of the Merensky Reef. However, the nickel and copper grades of Merensky ore are an order of magnitude higher than those of UG-2 ore[2], as is shown in Table 2 and, when their value is accounted for, the values *in situ* are $54 for Merensky ore and $57 for UG-2 ore. At present, UG-2 ore is not exploited for its chromite content, but the chromite value *in situ* is approximately $15 per tonne. If ferrochromium was to be produced on site (the feasibility of smelting UG-2 chromite has been shown[5]), this value would rise appreciably.

A comparison of gold ores and Merensky and UG-2 ores shows the following. The potential value of gold in gold ores is similar to that of the noble metals in Merensky and UG-2 ores. One gram of gold has a value of $10.29 (at $320 per ounce), and 1 g of total noble metals (containing the individual metals in the proportions

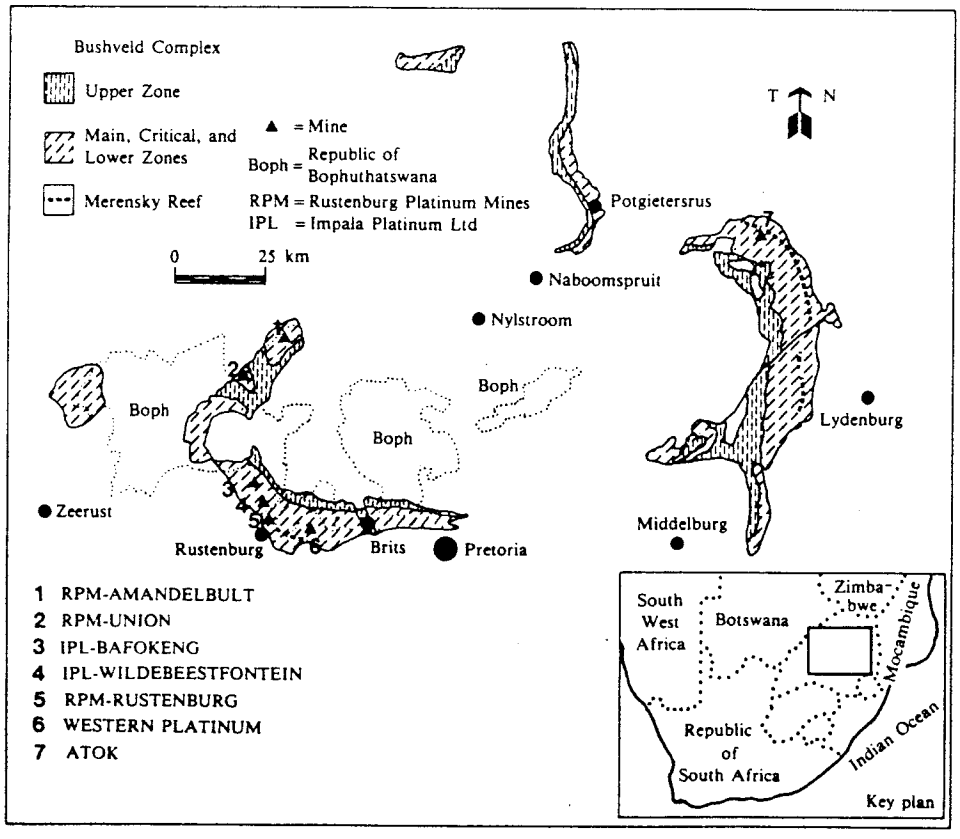


Fig. 1. Location of the major noble-metal mines in the Bushveld Complex. (After the Minerals Bureau of South Africa[1])

TABLE 1. *Relative proportions and values of noble metals in UG-2 and Merensky ore*

Noble metal	UG-2 ore[1] Content g/t	UG-2 ore[1] Distn %	Merensky ore[1] Content g/t	Merensky ore[1] Distn %	Market price* $/tr. oz.	Value in ore $/t UG-2	Value in ore $/t Merensky
Pt	2.46	41.0	3.24	59.2	256	20.24	26.67
Pd	2.04	34.0	1.37	25.0	116.5	7.64	5.13
Ru	0.72	12.0	0.44	8.0	165	3.82	2.13
Rh	0.54	9.0	0.16	2.9	1100	19.10	5.66
Ir	0.11	1.8	0.06	1.1	600	2.12	1.16
Os	0.10	1.7	0.04	0.7	900	2.89	1.16
Au	0.03	0.5	0.17	3.1	290.5	0.28	1.59
Total	6.00		5.43			56.09	43.50

* At 28th February, 1985

TABLE 2. *Content and value of base metals in UG-2 and Merensky ores*

Metal	Base-metal content of ore[2] % UG-2	Base-metal content of ore[2] % Merensky	Market price* $/t	Value in ore $/t UG-2	Value in ore $/t Merensky
Nickel	0.025	0.18	4964	1.24	8.94
Copper	0.01	0.13	1336	0.13	1.74
Total				1.37	10.68

* At 28th February, 1985

shown in Table 1) has values of $7.94 and $9.35 for Merensky and UG-2 ores respectively. The mining costs are much higher for gold ores than for Merensky and UG-2 ores because they occur at greater depth, but the processing of a gold ore is simpler and cheaper, and higher recoveries are generally obtained. Only 1 month elapses between the delivery of gold ore to the surface and the receipt of revenue for the finished product, whereas the lock-up of noble-metal values in the processing of Merensky and UG-2 ores exceeds 6 months.

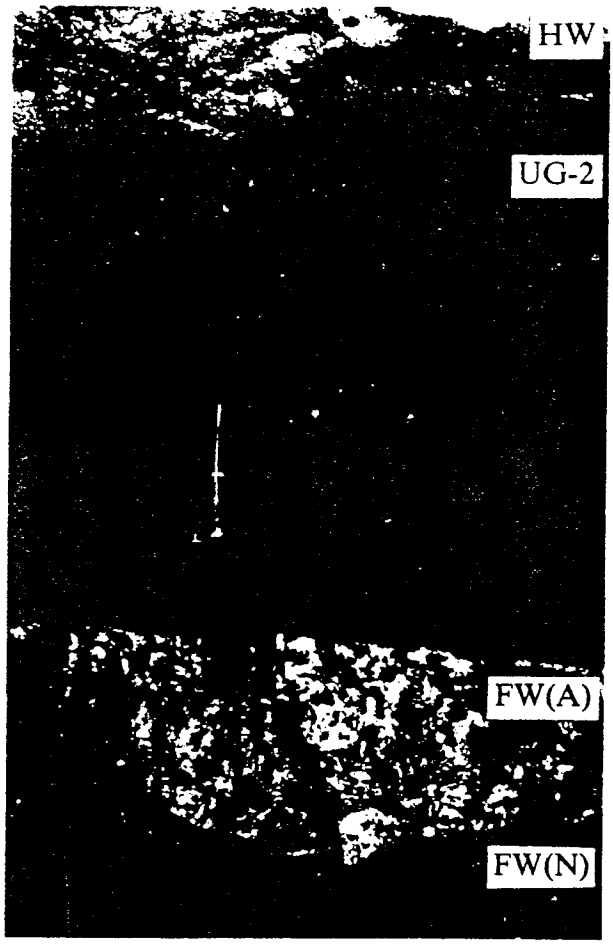
GEOLOGY AND MINERALOGY

General

The Merensky Reef is a pyroxenitic layer, which lies between footwalls and hanging walls of spotted and mottled anorthosite. Its thickness ranges from 0.6 to 15 m; where it is narrow, the noble-metal values occur throughout and where it is thicker, they are mostly found close to the hanging wall. Two chromitite stringers, which vary in thickness from a few millimetres to approximately 60 mm, are present in the Reef. The sulphide mineralization tends to be associated with these stringers. The upper stringer generally contains economic noble-metal mineralization, and mining operations include this chromitite. Secondary talc is widespread, occurring especially at the grain boundaries between sulphides and pyroxenes. The amount is variable up to 20 per cent and tends to decrease with depth[6]. The major silicate minerals[6,7] are orthopyroxene (50 to 70 per cent), plagioclase (11 to 25 per cent), and clinopyroxene (2 to 27 per cent).

The UG-2 Reef is a platiniferous chromitite seam that is conformable with the Merensky Reef but lies approximately 150 m below it in the western Bushveld and 330 m below it in the east. The main constituent (60 to 90 per cent) of the UG-2 Reef is chromite $[(Fe^{2+}.Mg)O.(Cr.Fe^{3+}.Al)O_3]$, which has a chromium-to-iron ratio of approximately 1.35.[8] The major silicate gangue minerals are orthopyroxene and plagioclase (30 to 50 per cent), while minor amounts of talc, chlorite, and phlogopite are present.

The hanging-wall contact with melanorite is well defined. However, the footwall has an undulating contact with norite, and a layer of coarse grained anorthosite and pyroxenite, which is commonly present between the chromitite and the norite, carries varying amounts of noble metals. This is illustrated in Fig. 2. Large inclusions of gangue are often present, and it is also fairly common for the pyroxenite footwall to have conformable inclusions in the base of the seam.



HW = Hanging wall (melanorite)
FW(A) = Footwall (anorthosite)
FW(N) = Footwall (norite)

Fig. 2. Part of the UG-2 Reef

Sulphide Mineralogy

In Merensky ore, the major base-metal sulphide is pyrrhotite (45 per cent). Also present are pentlandite (32 per cent), chalcopyrite (16 per cent), pyrite (2 to 4 per cent), and minor amounts of other sulphides.[6,7] The sulphides occur mostly in the interstices of the silicate grains, and sulphide inclusions in silicates and oxides are also present to some extent.

In UG-2 ore the major base-metal sulphide present[9] is pentlandite. Pyrrhotite and chalcopyrite are found in subordinate amounts, and millerite and pyrite in minor amounts. These sulphides generally occur at the grain boundaries of the gangue minerals and in the interstices of chromite grains. They are also found partially and totally enclosed in the chromite and silicate minerals. The sulphide grains of the UG-2 Reef are generally finer than those of the Merensky Reef. During flotation, the grain size of the UG-2 sulphides has been found to affect grade and recovery, which are lower for the smaller grains.

PGM Mineralogy

The PGM mineralogy of both reefs is complex, and varies with location. The PGM minerals are mostly associated with base-metal sulphides as occlusions, intergrowths, and in solid solution in the sulphides. In the Merensky Reef, PGM values are absent where no sulphides occur, but the converse is not true. More than 20 PGM minerals have been identified, and their relative abundance varies from place to place in both reefs. The more common PGM minerals are sulphides of the individual PGM or combinations of the PGM. A comparison of the PGM minerals occurring in the Merensky and UG-2 Reefs at various locations is given in Table 3.

The majority of the PGM minerals in Merensky ore are associated with pentlandite, occurring either in pentlandite grains or, more often, at the grain boundary of pentlandite with gangue. The average grain size of the PGM minerals has been given[7] as 236 (± 45)μm.

Mineralogical studies of UG-2 ore indicate that 70 to 80 per cent of the PGM minerals are associated with the base-metal sulphides[9], although the affinity for pentlandite is not so marked; 10 to 20 per cent are disseminated in the silicate gangue, and 5 per cent in the chromite. Laurite is commonly found included in chromite grains. The PGM minerals may also occur as single grains and aggregates along the grain boundaries of two or more chromite grains, or along chromite grains in contact with gangue particles. The grain size of the PGM minerals is smaller (usually by an order of magnitude) than that of the base-metal sulphides. The average grain size[4] is smaller than 15 μm, which is much smaller than that of Merensky ore.

MINING

Merensky and UG-2 ores are generally mined by the breast stoping method. A raise is developed along the dip from which gullies are cut into the orebody along the strike to form panels from which the ore is extracted. An alternative method, practised on Merensky ore, reduces the amount of scraping required to transfer the blasted ore to the boxhole. The mining costs for UG-2 ore are lower than for Merensky ore because UG-2 ore has a higher density (4.2 t/m^3) than Merensky ore (3.2 t/m^3).

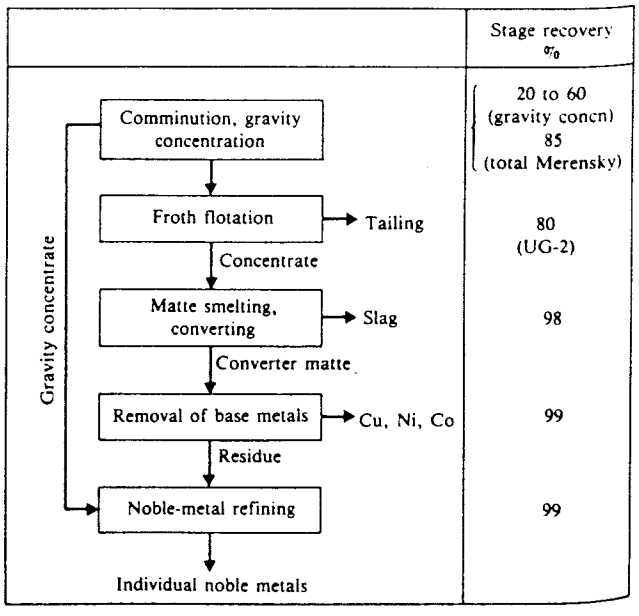
Table 4 shows that the noble-metal distribution in the size fraction of run-of-mine (ROM) ore differs for the two reefs. For Merensky ore, the noble-metal distribution follows the mass distribution, indicating that the values are evenly disseminated. The particle size of UG-2 ROM ore is finer than that of Merensky ROM ore, and the noble-metal distribution in the finer sizes of UG-2 ROM ore is greater than the mass distribution. This indicates that minerals containing the noble metals are liberated during mining, owing to the mineralization and friability of the ore. The majority of the sulphides are contained in the interstices of the chromite and silicate grains, and blasting and scraping liberate these sulphides at a fine size. Hence, not only does UG-2 ROM ore contain more fines than Merensky ROM ore, but the fines it contains are enriched in PGM. It is of interest that the grade of the slime fraction (<15 μm) of UG-2 ROM ore is ten times higher than the head grade.

The floatability of the ROM ores from both reefs decreases with particle size. This poses no problems for Merensky ROM ore, since it contains comparatively few fines. Unfortunately, this is not true for UG-2 ROM ore. Samples of the individual size fractions from each ROM ore were crushed, milled, and subjected to standard batch-flotation tests. The results are compared in Table 5, and it can be seen that the fine fractions give lower recoveries than do the coarse fractions. This reduces the overall recovery for UG-2 ore because the fine fraction contains larger amounts of noble metals.

These results suggest that, in the mining of UG-2 ore, consideration should be given to the use of underground blasting and handling methods that minimize the production of fines.

EXTRACTIVE METALLURGY

The process route used for gold ores involves direct leaching of the gold from the ore after suitable size reduction. This type of route would not be economically feasible for the processing of Merensky and UG-2 ores, because they would require pretreatment, e.g. chlorination, before being subjected to a leach under harsh conditions to dissolve all the noble metals. The process route followed involves preconcentration of the noble metals, smelting of the concentrate, and removal of the base metals before the individual noble metals are separated and refined. A general process route is shown in Fig. 3.



Note: Gravity concentration is applied only to Merensky ore

Fig. 3. General process route for Merensky and UG-2 ores

TABLE 3. *Relative abundance of PGM minerals in the Merensky and UG-2 Reefs at various locations*

PGM mineral		Merensky Reef[6]			UG-2 Reef		
Name	Chemical composition	Marikana	Northam	Rustenburg	Atok	Brits	Marikana[4]
Cooperite	PtS	10	Minor	Common	25	Minor	Common
Braggite	(Pt,Pd,Ni)S	7	Minor	Common	60	Minor	Common
Laurite	RuS_2	1	Common	Rare	5	Common	Common
Sperrylite	$PtAs_2$	50	Minor	Minor	2	Rare	Minor
Alloy	Pt–Fe	6	Common	Minor	2	Rare	Minor
Moncheite	Pt(Te,Bi)	13	Rare	Rare	5	Rare	n.o.
Kotulskite	(Pt,Pd)(Te,Bi)	8	Rare	Rare	n.o.	Rare	n.o.
Unnamed	(Pt,Pd,Cu)S	–	–	–	–	Common	Minor

n.o. not observed

TABLE 4. *Distribution of the noble-metals in Merensky and UG-2 run-of-mine ore*

Size fraction mm	Merensky ROM ore		UG-2 ROM ore	
	Cum. mass %	Cum. noble-metal %	Cum. mass %	Cum. noble-metal %
<12.5>1.7	36.5	35.3	65.3	62.7
< 1.7>0.075	3.0	5.0	41.8	32.8
<0.075	1.5	2.0	6.9	18.9

TABLE 5. *Individual flotation recoveries from various size fractions of run-of-mine ore and their contribution to overall recovery*

Size fraction mm	Merensky ROM ore			UG-2 ROM ore		
	PGM distn %	Recovery %	Contribution to total recovery %	PGM distn %	Recovery %	Contribution to total recovery %
>12.5	64.7	84.7	54.8	37.3	73.7	27.5
<12.5>1.7	30.3	80.8	24.5	29.9	69.1	20.7
< 1.7	5.0	76.1	3.8	32.8	66.6	21.8

This general route is the same for Merensky and UG-2 ores, but the operating conditions of the individual unit operations differ, because of the differences in mineralogical composition of the two ores.

Preconcentration

Comminution and Classification

Merensky ore can be comminuted in a conventional circuit, including crushing, rod milling, and ball milling, or by autogenous milling.[10] UG-2 ore is not amenable to autogenous milling, because its friable nature does not permit formation of the necessary competent pebbles. A small proportion of UG-2 ore (20 per cent) can be mixed with Merensky ore and the composite feed can be milled autogenously. Comminution of the UG-2 ore alone requires a circuit involving crushing, rod milling, and ball milling.

The mill product is classified in hydrocyclones. In a milling circuit for Merensky ore, the cyclone underflow is enriched in noble metals, and, as a result, so is the circulating load. This is to be expected when dense minerals are classified in this manner, but it can lead to overgrinding of the noble-metal minerals, with resulting losses in the subsequent preconcentration stages. The opposite effect is observed in a cyclone classifying UG-2 ore, where the underflow is depleted of noble metals and enriched in chromite. This is due to a number of factors. In UG-2 ore, the noble-metal minerals are contained in smaller sulphide particles, and are much finer than in Merensky ore. Also, a large proportion of the noble-metal minerals in UG-2 ore are liberated in the mining, crushing, and rod-milling operations. Although these minerals may be dense, they are small enough in relation to the cyclone cut size for them to pass to the overflow. Because of the large amount of chromite present (relative density 4.5 to

4.3) the coarse, lighter silicates report to the cyclone overflow. Hence, the silicates are not ground fine enough, and the sulphides they contain are not liberated and are lost to the tailings.

UG-2 ore therefore requires finer grinding than Merensky ore to liberate the sulphides. A comparison of the size and noble-metal distribution of the respective cyclone overflows is given in Table 6. The majority of the noble metals in Merensky ore are in the fraction between 150 and 38 μm, whereas the majority of the noble metals in UG-2 ore are in the fraction smaller than 38 μm.

TABLE 6. *Distribution of the noble-metals in Merensky and UG-2 cyclone overflows*

Size fraction μm	Merensky		UG-2	
	Cum. mass %	Cum. noble-metal %	Cum. mass %	Cum. noble-metal %
<300	98.7	-	100	100
<150	83.3	94.6	97.9	98.6
< 75	39.2	66.5	84.3	89.5
< 33	8.1	14.2	58.4	74.9
< 10	-	-	21.2	28.5

Preconcentration in the Milling Circuit

Because the cyclone underflow in a Merensky milling circuit is enriched in noble metals it is advantageous for the noble-metal minerals to be removed before they are overground. This also has the advantage that, after the concentrate has been upgraded, it can be sent direct to the PGM refinery, thus by-passing the intermediate stages. This naturally results in a more rapid generation of revenue.

Originally, corduroy strakes were used to concentrate the noble metals, and further upgrading of the concentrate was accomplished on James tables. However, chromite is also recovered by the strakes and had to be removed before the concentrate was sent to the PGM refinery. The use of strakes has the further disadvantage that they are labour-intensive and that security can be a problem. As an alternative to strakes, the unit flotation cell (e.g. the Davcra, which has no moving mechanisms) can be used to concentrate the noble metals, and the concentrate, which contains very little chromite, can be upgraded on James tables.

UG-2 ore is not as amenable as Merensky ore to preconcentration in the milling circuit because a much finer grind is needed to liberate the noble-metal minerals and because the chromite present can lead to poor separation.

Flotation

For Merensky and UG-2 ores, the flotation process is a bulk sulphide float that recovers the base-metal sulphides containing noble-metal minerals and any liberated PGM sulphide minerals. Alloys of noble metals and other metals are not recovered and, if these are present in the ore in large amounts, the flotation recovery will be reduced. Flotation takes place at natural pH (7.5 to 9) with a xanthate collector such as isobutyl xanthate or normal propyl xanthate. The general practice on most mines is the addition of another collector, usually Cyanamid 3477 (a dithiophosphate), which is mixed with the xanthate at a ratio of up to 7:3. Copper sulphate is added as an activator, generally to the milling circuit. However, when a Davcra cell is used this can lead to instability of the froth, so the copper sulphate is added to the cyclone overflow.

The flotation circuit for Merensky ore usually consists of a rougher stage and two cleaner stages, in which closed-circuit cleaners are used. To depress the talc, which is naturally floatable, a depressant is added to the rougher and cleaner stages. Dextrin was used originally, but has been replaced by modified carboxymethyl cellulose (CMC) and, more recently, by modified guar gums. Although the use of a silicate depressant is costly, being approximately $0.25 per tonne of feed, its need is demonstrated in Fig. 4, which compares the grade-recovery curves for two batch-flotation tests: one in which no depressant was added, and another in which a CMC was added to the rougher (299 g/t), cleaner (50 g/t), and recleaner (30 g/t) stages. The performance of a Merensky flotation plant can be monitored by the use of the nickel assays of various streams because the majority of the noble metals occur with the pentlandite.

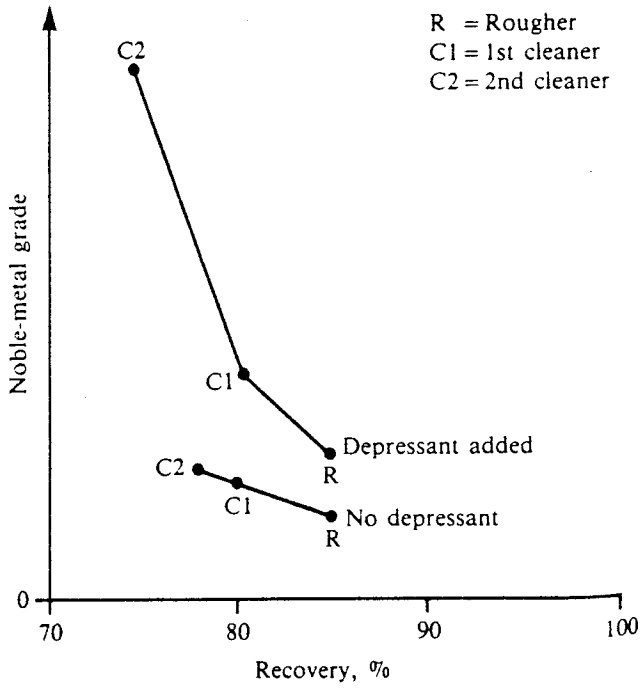


Fig. 4. Batch flotation of Merensky ore, showing the need for a silicate depressant

The flotation of UG-2 ore is similar in general principle to that of Merensky ore, but differs in a number of aspects. The major gangue in UG-2 ore is chromite, and a constraint on the plant operation is that the chromic oxide (Cr_2O_3) content of the concentrate should not exceed 3 per cent. The chromite content of the concentrate is controlled by the use of three cleaning stages and of a frother that produces a brittle froth, which reduces the amount of physically entrained chromite.[11,12] A silicate depressant may be necessary if talc is present in large quantities.

The mass percentage of UG-2 concentrate is lower than that of Merensky concentrate. Hence, the UG-2 grades are higher, and the amount of concentrate to be smelted is smaller. A comparison of the concentrates is given in Table 7.

The fine sulphides in the UG-2 flotation circuit have slow flotation rates, and the cleaner circuit must have a large volume to ensure that the residence time of these particles is sufficiently long, otherwise they recirculate to the rougher stage and are eventually lost to the rougher tailing.

The size distribution of the noble metals in the Merensky and UG-2 flotation tailings are shown in Table 8, from which it can be seen that both tailings contain a large proportion of noble metals in the fraction smaller than 10 μm. These slimes in the Merensky tailings are caused mainly by overgrinding of the sulphides in the milling circuit, whereas the slimes for the UG-2 tailings were mostly present in the ROM ore.

Both tailings also contain large proportions of noble metals in the coarser size fractions, due to poor liberation of the sulphides from the silicates. In the Merensky tailings, the fraction larger than 75 μm contains 41.5 per cent of the noble metals and the corresponding fraction of the UG-2 tailings 27.3 per cent. The percentage is higher for the Merensky tailings because the grind is coarser, and because the silicate depressant prevents chatted particles, which would otherise float, from reporting to the concentrate. If the coarse fraction is removed from the UG-2 tailings, reground, and refloated, over 80 per cent of the noble metals can be recovered. This coarse fraction contains relatively little chromite and the refloat is similar to Merensky float.

The flotation response of UG-2 ore from different locations varies. This is shown by Fig. 5, which compares the grade-recovery curves for two samples that have the same type of footwall and that were taken from locations in close proximity to each other. The main difference between the samples is in the grain size of the sulphides. The ore from which the poorer results were obtained (lower curve) contains finer sulphide grains, alloys of the noble metals and iron that do not float if liberated, and a talc-chlorite silicate that may account for the low grade of the concentrate.

Smelting

Smelting is intended to separate the gangue (oxide) minerals and the sulphide minerals containing the noble metals. The sulphide minerals form a matte, which is then treated further; the gangue, which has been fluxed with limestone, is discarded as slag.

The flotation concentrate can be filtered and partially dried to a moisture content of 5 per cent before being fed to the furnace. More commonly, the concentrate is agglomerated by pelletizing or spray drying, which reduces dust losses and provides a porous charge through which reaction gases arising from decomposition of the sulphides can escape.

The Merensky concentrate is smelted in a rectangular electric submerged-arc furnace that has six Søderberg electrodes in line.[10,13,14] One smelter treats 420 t (dry) of concentrate per day in an 18.5 MVA furnace[13]; another treats 220 t per day in a 7.5 MVA furnace.[14] As the concentrate and the added flux melt, two liquid phases form: a slag with a relative density of approximately 2.7 and a matte with a relative density of 5.3. The prills of molten matte grow in size by coalescing with other prills, and then settle out from the slag under the influence of gravity. The rate of settling is a function of the prill size and slag viscosity. The flux is added to the charge to reduce the

TABLE 7. *Comparison of the Merensky and UG-2 flotation concentrates*

Flotation concentrate	Conct. as mass % of feed	Total noble metals g/t	Ni %	Cu %	S %	Cr_2O_3 %
Merensky	2.5	100 to 250	3.2	2.1	9.0	0.3
UG-2	1.3	300 to 600	1.7	0.75	3.6	2.9

TABLE 8. *Distribution of the noble-metals in a Merensky and a UG-2 flotation tailing*

Size fraction μm	Merensky		UG-2	
	Cum. mass %	Cum. noble-metals %	Cum. mass %	Cum. noble-metals %
<212	95.6	90.3	99.6	99.5
<150	85.4	71.8	97.0	90.8
<106	66.3	58.5	90.6	72.7
< 75	51.9	46.1	79.6	57.5
< 53	40.2	36.8	59.8	44.7
< 38	29.1	29.8	46.6	37.6
< 20	18.4	23.1	21.1	27.2
< 10	8.5	19.0	11.8	22.4

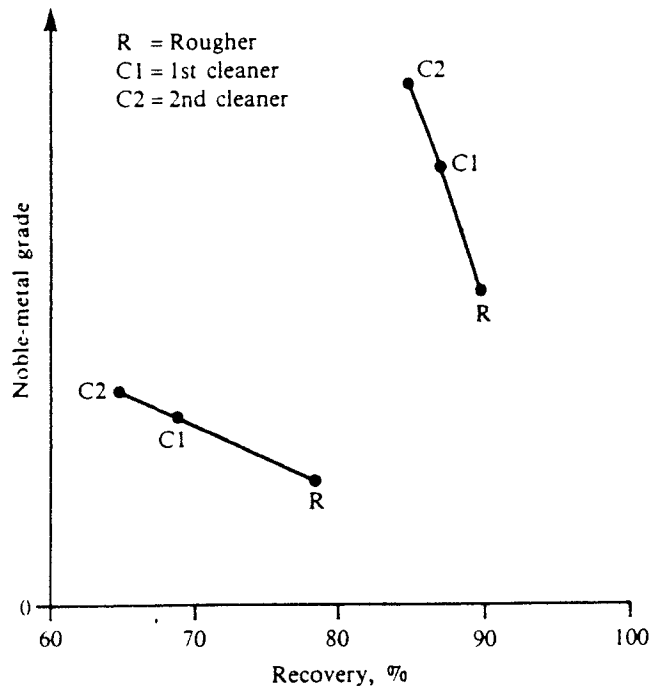


Fig. 5. Comparison of grade-recovery curves for two samples of UG-2 ore, showing the variability in flotation response over short distances

melting point of the slag and, hence, its viscosity at operating temperature. The rectangular furnace is provided with a settling zone for the matte between the last electrode and the slag-tapping end. In practice, slags containing about 0.54 g of the noble metals per tonne[13] are tapped from the furnace; this value is low enough for the slag to be discarded.

The matte produced from the furnace is transferred in the molten state to a Pierce-Smith converter. The iron sulphide is oxidized to wustite (FeO), and the sulphur is removed as SO_2. The wustite that forms is reacted with silica sand to produce a fayalite [$(FeO)_2SiO_2$] slag. The converter slag has a high PGM content due to entrained prills, and is returned to the matte-smelting furnace for their recovery. The fayalite slag has a beneficial effect in that it lowers the liquidus temperature of the slag formed in the matte-smelting furnace, but the converter slag also contains a proportion of magnetite, which is formed at the start of the blow when the converter is still cold. This magnetite can settle out and precipitate on the furnace hearth, thus considerably reducing the volume of the furnace in time. Samples of the accretions deposited on the hearth of the furnace have also been shown to contain a proportion of chromic oxide, which is present predominantly as chromite. It has been suggested that the source of this chromic oxide is the chromium–magnesite refractories used in the converter and the chromic oxide in the Merensky concentrate. The deposition of accretions in the hearth occurs even in well-run operations. It was feared, therefore, that the smelting of UG-2 concentrate, a feed material with an even higher chromium oxide content, would not be possible by conventional smelting technology.

A comparison of the metal oxide content of the flotation concentrates is shown in Table 9, and the higher concentrations of MgO, SiO, and Al_2O_3 in the UG-2 concentrate indicate that higher smelting temperatures and, possibly, larger additions of flux would be necessary for the production of a slag with a viscosity low enough for an acceptable separation of the matte and the slag to take place. The chromic oxide content of the UG-2 concentrate is almost ten times that of the Merensky concentrate and, if allowed to deposit in the furnace hearth, would rapidly build up and reduce the volume of the furnace.

Laboratory- and pilot-scale tests in a 200 kW single-phase arc furnace indicates that adequate coalescence of the matte prills could be obtained by the use of a higher smelting temperature and power density (watts per square metre of the furnace area) to increase turbulence in the bath. The chromic oxide would then dissolve in the matte and the slag and would be removed from the furnace on tapping. Therefore, a circular electric furnace with three graphite electrodes is more suited to the smelting of UG-2 concentrates since it can better withstand operation at the higher power density and temperature required.

The absence of a settling zone in the circular furnace results in a slag with a PGM content of 2.5 to 3.5 g/t, which is too high for the slag to be discarded; it can be granulated and returned to the flotation circuit for recovery of the PGM. The build up of chromite in the hearth can be reduced by the blending of some Merensky concentrate with the furnace feed. Unlike the walls of the rectangular furnace, those of the circular furnace are not protected by banks of unmelted charge. Therefore, for reduced erosion of the furnace lining, the UG-2 slag must have a higher basicity to make it compatible with the basic refractory used. Typical slag analyses are given in Table 10.

During pilot-plant tests in the 200 kW furnace, some comparative tests were done on the electrical energy requirements for smelting. In these tests, similar methods were used for the smelting of Merensky and UG-2 concentrates, and it was found that 396 kW.h is required per tonne of Merensky concentrate, whereas 1088 kW.h is required per tonne of UG-2 concentrate. The average temperature of the UG-2 slag during these tests was 1474 °C, and that of the matte 1300 °C. These temperatures are higher than those normally obtained in conventional matte smelting in a six-in-line furnace, i.e. between 1340 and 1350 °C for the slag, and 1150 and 1245 °C for the matte.

The UG-2 matte is blown in a manner similar to that used for the Merensky matte, and the two mattes can be mixed beforehand, although this may cause problems if the blown matte is to be slow-cooled to form a nickel phase.

Slow cooling of the blown matte causes the separation and crystallization of a nickel phase, which acts as a collector for the noble metals. Hence it can be used to concentrate the majority of the noble metals before the removal of the base metals. The cooled matte is then crushed and milled, and the nickel phase containing the noble metals is recovered by magnetic separation. Separate leaching of the nickel and any sulphides leaves a high-grade (50 per cent) noble-metal concentrate, which is treated in the PGM refinery. For the Merensky matte, the magnetic nickel product represents 12 per cent of the mass and contains over 95 per cent of the noble metals but, for a UG-2 matte, the phase separation is not as efficient, and the nickel phase, which represents 10 per cent of the mass, contains only 50 per cent of the noble metals.

TABLE 9. *The metal oxide contents of Merensky and UG-2 concentrates*

Concentrate	CaO %	MgO %	SiO_2 %	Al_2O_3 %	FeO %	Cr_2O_3 %
Merensky	2.20	18.2	41.4	1.62	22.3	0.3
UG-2	2.40	21.0	44.0	5.00	12.6	2.9

TABLE 10. *Analyses of Merensky and UG-2 furnace slag*

Furnace slag	CaO %	MgO %	SiO_2 %	FeO %	Cr_2O_3 %	$\frac{CaO + MgO^*}{SiO_2}$ %
Merensky (mine A)	15	15	41	20	-	0.73
Merensky (mine B)	8	13	47	23	-	0.55
UG-2 (mine B)	16	20	43	14	1.5	0.83

* Basicity

Mixing of the mattes prior to converting causes the nickel phase to collect approximately 90 to 95 per cent of the noble metals, but the mass of this phase rises to 25 per cent.[15] The blown matte or the non-magnetic fraction that results from slow cooling then passes to the base-metal refinery where the base metals are removed to leave a noble-metal residue.

Removal of Base Metals

The original method used for the separation of the copper and nickel was the Orford or 'top and bottom' process[16], in which the matte is smelted with sodium sulphide. This causes the copper sulphide and nickel sulphide phases to become immiscible and to separate. After separation of the phases, the copper sulphide phase is converted to blister copper, which is cast into anodes and refined electrolytically. Any noble metals present report to the anode slime. The nickel sulphide phase, which contains the majority of the noble metals, is milled, roasted, reduced to metal, and refined electrolytically. The anode slime is then mixed with the anode slime from the copper refining, and the mixture is roasted and leached with sulphuric acid to remove the base metals and to leave a noble-metal residue, which is sent to the PGM refinery.

Nowadays, it is more common for the base metals to be removed from the matte and hydrometallurgical routes, and variations of the Sherritt Gordon and Falconbridge methods are employed.

The Sherritt Gordon process is a pressurized oxidative leach in which the finely ground matte is leached in a number of stages to produce nickel- and copper-rich solutions and a noble-metal residue. The first leach with sulphuric acid under mildly acidic conditions dissolves as much nickel as possible without dissolving too much copper. The nickel solution is purified by the precipitation of copper with sodium hydrosulphide, and of iron with ammonia and air. The nickel can then be recovered electrolytically, the metal being precipitated by pressurized hydrogen reduction, or it can be crystallized as nickel sulphate. The residue from the first-stage leach is then subjected to a leach under harsher conditions to dissolve the copper and any remaining nickel, and the copper solution is passed to a copper electrowinning circuit. The residue can be subjected to another leach to upgrade the noble-metal content before the final residue passes to the PGM refinery.

The Falconbridge process consists of a non-oxidative leach with hydrochloric acid at normal temperature and pressure to dissolve the nickel, iron, and cobalt. The solution is oxidized with air to remove the sulphur, and the iron and cobalt are removed by solvent extraction. The nickel is then recovered and the hydrochloric acid is regenerated. Calcination of the residue from the nickel leach oxidizes the copper sulphide to its oxide, which is then leached with sulphuric acid. After solid–liquid separation, the copper is electrowon from the solution and the residue passes to the PGM refinery.

Refining of the Noble Metals

The original noble-metal refining process used a technique involving the selective crystallization of complex salts of the individual elements[16,17], which were then removed by filtration and purified further by successive dissolution and recrystallization. Where applicable, the metals were finally produced in their pure form by calcination of the purified precipitates. The flowsheet for the initial separation of the noble metals by this method is shown in Fig. 6. The stage efficiencies of this process are generally fairly low, and the purification steps need to be repeated several times. This generates a larger number of recycle streams and extends the lock-up time, especially for rhodium, ruthenium, osmium, and iridum (often called the 'other platinum metals' or OPM).

In the last 10 years, solvent extraction has become increasingly popular, and most of the refineries currently incorporate some solvent-extraction stages in their processes. This technique is more selective than the precipitation technique, and the correct number of mixer-settler units can be chosen to give a high extraction. The process also lends itself to more automation and, hence, less handling of corrosive liquids. At least three processes

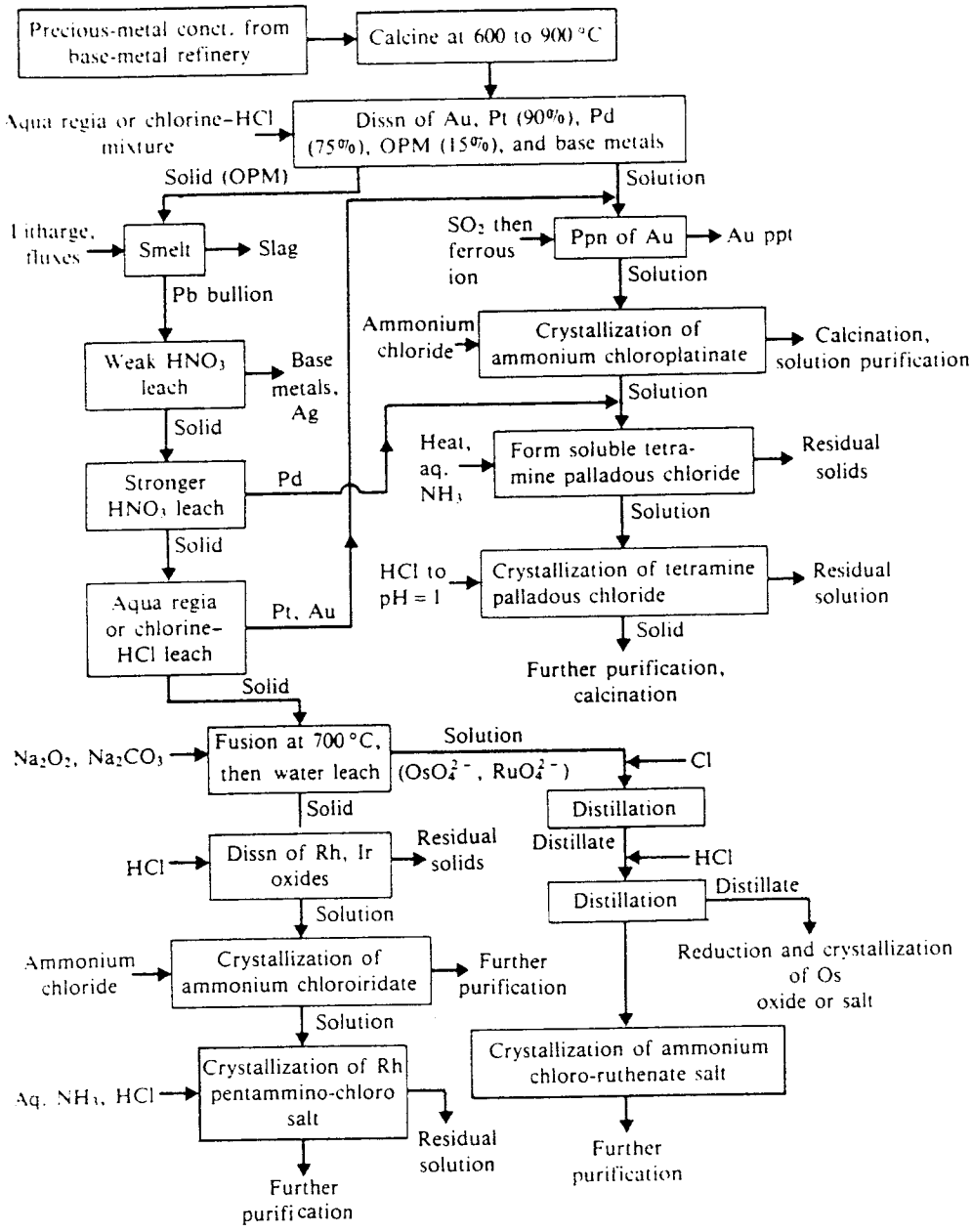


Fig. 6. Original flowsheet for the separation of the precious metals

Concl. = Concentrate
OPM = Rh, Ru, Os + Ir
Ppt = Precipitate
Ppn = Precipitation
Dissn = Dissolution

have been patented: The Opnim process (Council for Mineral Technology), the Inco process (International Nickel), and the MRR process (Matthey Rustenburg Refiners). Each process differs in the way that the OPM are rendered soluble, the order of extraction of the metals, and the way in which the individual metals are extracted.

In the Opnim and Inco processes, most of the platinum and palladium are dissolved first with aqua regia or a mixture of chlorine and hydrochloric acid. In the Opnim process, the platinum and palladium are then recovered by crystallization of the chloro-ammonium salts whereas, in the Inco process, the leach liquor is combined with that resulting from the dissolution of the OPM-bearing residue. In the Opnim process, the OPM-bearing residue resulting from the dissolution of the platinum and palladium is alloyed with aluminium and some iron and after removal of the base metals with hydrochloric acid, the OPM are leached with chlorine–hydrochloric acid. In the Inco process, the OPM-bearing residue is fused with sodium peroxide and sodium carbonate, which renders the OPM soluble. In the MRR process, the residue from the base-metal refinery is subjected to high temperature dry chlorination (before any noble metals are leached) to render the OPM soluble in chlorine–hydrochloric acid. A brief comparison of the extraction methods used in each process[17,18] is given in Table 11. Ion exchange can be used to concentrate and to purify low-grade solutions of gold, iridium, and rhodium after solvent extraction.

CONCLUSIONS

Although the same basic route is used for the processing of Merensky and UG-2 ores, the operating conditions

TABLE 11. *Comparison of various modern processes for separation of the noble metals*

OPNIM	INCO	MRR
Most Pt, Pd dissolved and crystallized *Au* Carrier: 6 M HCl Solvent: isodecanol Strip: alkali *Pd* Solvent: di-n-hexyl sulphide Strip: 15% NH_3 solution Os, Ru, Ir reduced with SO_2 *Pt* Solvent: amine or TBP Strip: 6 M HCl *Os* Boiled with HNO_3; OsO_4 volatilized Reduced with formic acid *Ru* Solvent: TBP or amine Strip: water Oxidized with chlorine *Ir* Solvent: TBP Strip: water *Rh* Crystallized as pentamine salt with NH_3	3-stage leach to dissolve all noble metals *Os, Ru* distilled as tetroxides *Au* Solvent: dibutyl carbitol *Pd* Solvent: di-octyl-sulphide Reduced with SO_2 *Pt* Solvent: TBP *Ir* Crystallized as ammonium salt *Rh* Crystallized as pentamine salt	All noble metals dissolved by chlorine HCl *Au* Solvent: MIBK Strip: direct cementation *Pd* Solvent: LIX64N + amine Strip: 6 M HCl *Os, Ru* distilled as tetroxides Reduction *Pt* Solvent: Amberlite LA2 (amine) Oxidized *Ir* Solvent: amine Strip: water, SO_2 *Rh* Solution concentrated by ion exchange, then crystallized as pentamine salt

for the unit operations differ. This is mainly because of the differences in the major gangue minerals and in the grain sizes of the sulphides and noble-metal minerals. The processing of UG-2 ore is more difficult than that of Merensky ore, and the overall recoveries are lower. However, UG-2 ore has the advantages of a higher value *in situ*, lower mining costs, and a chromite content that is a potentially saleable product. However, UG-2 ore has the disadvantage that the fine grain size of the sulphides and noble-metal minerals precludes their concentration by unit flotation or gravity methods in the milling circuit, which means that all the noble metals have to pass through the smelting and base-metal refining stages. If the process route does not include a gravity-concentration stage, and the ore being treated contains a large amount of noble-metal alloys, which are not recovered by flotation, the overall recovery will be reduced.

In the smelting, base-metal removal, and noble-metal-refining stages, the percentage recoveries of the noble metals from both ores are in the upper nineties. Further improvement, therefore, would be difficult. The potential for improved recovery lies in the preconcentration stage, especially of UG-2 ore, for which recoveries are lower than for Merensky ore. For both ores, the potential for increased recovery lies in the treatment of the coarse (larger than 75 μm) fraction of the flotation tailing, where the noble-metal values are not liberated from the gangue.

Some of the mines that have been engaged mainly in treating Merensky ore have found that the Merensky workings are becoming deeper, and that UG-2 ore can be mined at a shallower depth with the same facilities. Therefore it is a reasonable assumption that, in future, the UG-2 Reef will be mined to an increasing extent. Gold Fields of South Africa Limited recently announced that they are investigating the possibility of exploiting the Merensky and UG-2 Reefs in the Northam area, where they hope to produce 13 000 kg of noble metals per year. If this is possible, Southern Africa (the Republic of South Africa and Bophuthatswana) will become the World's largest producer of the noble metals.

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