

cent press reports, Impala's mines presently derive some 42 per cent of their ore from the UG2, compared to Western Platinum's 73 per cent, the balance being from the Merensky.

4.2. Beneficiation Processes

The extraction of the valuable metals from the ore takes place in five distinct steps.

- The ore is comminuted and a gravity concentrate is extracted.
- The valuable sulphides are concentrated by flotation.
- The flotation concentrates are smelted to produce a copper-nickel matte.
- Hydrometallurgical treatment of the matte follows, to separate the base metals from the precious metals.
- Finally, the concentrate is refined to separate the individual PGM and gold in their pure forms.

In the discussion that follows, processing methods are confined to those practised by South African procedures, with which the author is familiar.

Each processing step is designed to increase the grade of the economic components of the original ore, while reducing the bulk of the products. As a rough guide, it is estimated that the successive steps contain the following percentages of the precious metals:

ore	0,00047	per cent	
flotation concentrate	0,015	per cent	
converter matte	0,20	per cent	
PGM concentrate	30,00	per cent	
refined metals	99,90	per cent	(ruthenium, rhodium and osmium)
Refined metals	99,95	per cent	(platinum, palladium, and gold).

The rapidly changing contents of silicate and ore minerals in the Merensky and UG2, and their relative densities, their morphology, relative particle size, and association are monitored by mineralogists on an ongoing basis. Vermaak and Hendriks, 1976, provide examples of such work. The results of the mineralogical investigation enable the metallurgists to optimize the primary extraction processes, particularly the fineness of grind required to liberate the valuable metals (usually as sulphides) from the silicate gangue. The ore mineralogy is neither constant along the strike of the orebody nor down-dip. The successive concentration processes do not differ radically from one mine to another, both in a local and in a global sense, although there can naturally be marked differences in such matters as the flotation and other reagents used, as well as in the smelting and refining processes, principally where the precious metals are byproducts of the mining of nickel-copper orebodies, such as in Russia and Canada.

4.2.1. Comminution and Gravity Concentration

Some of the ores are crushed coarsely by primary crushers underground before being hoisted to surface, where

crushing is undertaken by secondary open-stage and tertiary closed-circuit cone crushers and vibrating screens to provide a 18 mm product. Either semi-autogenous milling, single-stage ball milling, or two-stage rod and ball milling, with water as a carrier, is undertaken to produce a very fine-grained product. The original ores are relatively hard, with high bond indexes. Size reduction by milling in closed circuit, together with cyclone classifiers, can be required to produce a -75 µm (-200 mesh sizing), making up a 55 per cent proportion of the MR feedstock and an 80 per cent of the UG2 feedstock. This grinding and pulverizing serves to liberate the valuable minerals from the silicate gangue, with which they are intimately grown in the original MR or UG2 ores. The product is a fine-grained slurry, which may have to be either submitted to a second-stage grinding process to liberate all the minerals indicated in the mineralogical study, or, if the particles are sufficiently fine, may be pumped directly into the flotation cells. At most mines, however, the ore minerals are separated from the gangue by gravity methods using corduroy cloth tables and/or Davcr unit cells, each of which is followed by James tables. This produces a first-stage gravity concentrate containing up to 30 per cent of the precious minerals. This gravity concentrate, which is invariably produced from Merensky ores, can be sent directly to the refinery, thus omitting the subsequent concentrating steps. The UG2 ores, because of their high proportion of heavy chromite crystals, are not subjected to this gravity separation step.

4.2.2. Flotation

The froth-flotation process, which is similar to that used at nickel-copper sulphide mines in Russia and Canada, uses conventional flotation reagents such as xanthate collectors, copper sulphate modifiers, and traditional frothing agents. The flotation process makes use of the different surface characteristics of the ore minerals and the gangue particles to achieve a separation. Various chemicals are added to the slurry to make the ore-mineral particles hydrophobic or non-wettable, while retaining the wettable properties of the gangue particles. Other chemicals are added to create the required froth, and to suppress unwanted minerals (such as talc in the Merensky gangue). The slurry is then pumped into the flotation cells and vigorously agitated to produce a layer of froth containing the unwettable sulphide particles on the top, while all the wettable gangue minerals remain in the slurry. The froth is carefully collected in the overflow from the flotation cells and is allowed to thicken or settle, the contained water being drawn off and returned to the milling circuit. The waste slurry or tailings from the flotation cells is allowed to thicken in storage dams, where the water is drawn off and returned to the concentration plant. The UG2 tailings easily be upgraded to 40 per cent.

The sulphide concentrate from the froth has a PGM content of 100 to 400 g/t, depending on the original

nature and concentration of the copper-nickel sulphides with which the PGM are associated in the ore. The PGM and gold recovery is in the order of 80 to 87 per cent. A typical analysis of the MR and UG2 concentrates at Western Platinum Mines is as follows.

PGM, g/t	MR conct.	UG2 conct.
Ni, %	100-150	300-400
Cu, %	4-5	1-1,5
S, %	2,5-3	0,7-1
FeO, %	8,5-10	3,2-4
Cr ₂ O ₃ , %	20	16
Co, %	0,3	3,0
MgO, %	3	2
Al ₂ O ₃ , %	15	20
SiO ₂ , %	6	4
	39	43

4.2.3. Smelting

Depending on individual requirements the flotation concentrate is dried until it contains between 7 and 10 per cent moisture, after which it is pelletized and then dried further to between 2 and 4 per cent moisture. Regardless of the drying procedure used, the products are fed directly into a furnace and smelted. Differential settling in the melt produces a light silicate- and iron-rich slag (relative density 3,3) and a heavy molten matte (relative density 4,8) rich in nickel, copper, and other base and precious metals, which collects at the furnace base. The furnaces were originally heated by either coke, pulverized coal, oil, or natural gas, but the more modern furnaces include blast and reverberatory furnaces. Because of the relative cheapness of electricity in South Africa, submerged-arc furnaces with six aligned Söderberg-type electrodes are almost invariably used. Recently, circular furnaces have been employed.

The slag is tapped separately from the matte, either intermittently or continuously, at temperatures around 1350 °C. MR slag may be granulated and reloaded, and the concentrate returned to the furnace, depending on its useful base-metal or precious-metal content. Because of their high chromite content, UG2 concentrates are smelted separately, and the slag is usually retreated by milling and flotation because of its high metal content.

The molten matte from both the MR and UG2 furnaces is tapped at about 1200 °C and poured into ladles. At Western Platinum Mines, the Merensky and UG2 beneficiation circuits are separate up to the production of the furnace matte, but the matte from both types of furnace is added to the same ladle. The converter matte has a density of about 6, and contains about 48 per cent nickel, 29 per cent copper, from 21 to 22 per cent sulphur and small amounts of cobalt and precious metals. The quantity of PGM can vary from 1 to 30 g/t, depending on the constituent minerals in the ores. The matte also contains small amounts of selenium, tellurium, arsenic, lead, tin, antimony, and bismuth, but as far as is known, none of these are recovered for revenue purposes.

The ladles with the converter matte are now transported to Pierce-Smith type converters, where an auto-

genous blow of air or oxygen oxidizes any iron, which is removed by the addition of silica sand. The iron silicate so formed is usually returned to the smelting furnace. Any excess sulphur in the matte is oxidized by the blow to sulphur dioxide gas, which is recovered either as elemental sulphur or as sulphuric acid in order to obviate or minimize any atmospheric pollution.

The converter matte is chill-cast into ingots, and allowed to cool over 4 to 5 days to encourage the formation and separation of an iron-nickel phase and a copper-nickel alloy phase. This method of slow-cooling the matte, which can be routed to a separate enrichment circuit, considerably shortens the overall processing times and reduces the hold-up of the precious metals in the extraction and refining circuits. The iron-nickel phase can collect up to 95 per cent of the precious metals, thereby confirming their siderophile rather than their chalcophile characteristics. The resulting cooled matte is crushed to about a -15 mm size, and ground in a rubber-lined ball mill in closed circuit with a hydrocyclone until it consists of some 88 per cent of -75 µm or -200 mesh particles. The iron-rich part of that material, which contains the precious metals, is removed by passing it through a series of magnetic separators, leaving the copper-nickel-rich or base-metal portion behind.

The copper and nickel are extracted at the base-metal plant by either a chloride or a sulphuric-acid leaching route.

At the Noril'sk and the Canadian mines, the nickel is also extracted by the same method of slow-cooling the matte. The PGM-rich nickel metal is cast into anodes, the nickel then being refined by extraction in electrolytic cells. The impure nickel anodes dissolve in the electrolyte, thus releasing the nickel for deposition at the cathode. The PGM do not dissolve in the electrolyte, but are deposited as an iron-rich sludge at the base of the electrolytic cells. This sludge is then sent to the PGM refinery for further treatment.

At Western Platinum Mines, all the matte is processed at the base-metal refinery, using technology from Sherrit Gordon in Canada, to produce nickel sulphate crystals, pure copper cathodes, and a high-grade PGM concentrate.

4.2.4. Leaching and Chemical Separation

At most base-metal plants in South Africa, the converter matte is processed directly. The nickel and copper are separated by differential leaching in agitated tanks at atmospheric pressure and in autoclaves at high temperature and pressure.

In the *first-stage leach*, the main chemical reactions are aimed at removing nickel and copper by precipitation. This leach is carried out in five tanks arranged in cascade fashion using spent electrolyte, heated to 90 °C, from the electrowinning circuit, to which oxygen (also acting as an agitator) and sulphuric acid have been added. The new feed from the smelter is added to this solution and the solid/liquid separation of the nickel and copper takes place in a thickener. The thickener