

Developments in the application of carbon-in-pulp to the recovery of gold from South African ores

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SYNOPSIS

An account is given of developments in the use of activated carbon for the recovery of gold from cyanide solutions. The carbon-in-pulp process employed at the Homestake Mine is described, and its various applications in South Africa and their effectiveness are discussed. Probable future work on the carbon-in-pulp process and other possible applications of carbon for the recovery of gold are outlined.

SAMEVATTING

Die ontwikkeling van die gebruik van geaktiveerde koolstof vir die herwinning van goud uit sianiedoplossings word nagegaan. Die koolstof-in-pulpproses wat by die Homestake Mine toegepas word, word beskryf en die verskillende toepassings daarvan in Suid-Afrika en hul doeltreffendheid word bespreek. Moontlike toekomstige werk in verband met die koolstof-in-pulpproses en ander moontlike gebruike van koolstof vir die herwinning van goud word uiteengesit.

Introduction

The realization by MacArthur and the Forrest brothers in the 1890s that gold and silver dissolved in cyanide solutions and that zinc could be used to precipitate the dissolved gold was the beginning of our present-day system of gold recovery¹. Over the years, this basic system, although it has changed very little in principle, has been refined to become the highly efficient process that is used in the treatment of Witwatersrand gold ores.

By 1880, it was apparently known² that activated carbon (or charcoal) would adsorb or precipitate gold in the solutions resulting from gold chlorination. Soon after the introduction of the cyanide process, it was realized that activated carbon could be used to adsorb gold and silver from cyanide solutions. Johnston patented the use of carbon as a precipitant for gold from cyanide solutions in 1894. In 1916, carbon was used instead of zinc as a precipitant at the Yuanmi Mine in Western Australia⁴, where the pregnant solutions were pumped through three successive 'filters' containing very fine carbon. It is interesting to note that the theory^{5, 6} was advanced that the carbon was acting to adsorb the alkaline aurocyanide without any chemical change.

Two factors probably retarded the development of the use of carbon instead of zinc: firstly, there was no procedure for the elution and recycling of the loaded carbon (which was smelted for recovery of its gold content) and, secondly, the Crowe-Merrill procedure, in which gold is precipitated with zinc dust, was considered to be adequate. (The latter process has been developed to the point where the gold content of the barren solutions is less than 0,01 g/t⁷. It would be difficult to improve on such recoveries.)

An interesting development in the use of activated carbon for the recovery of gold was the process patented in 1939 by Chapman⁸, who added fine carbon to a

cyanided pulp to adsorb gold, and then recovered the loaded carbon by floating it with dieselene and a frother. The flotation concentrate was smelted so that the gold could be recovered. (It should be noted that developments along similar lines are now taking place on some Witwatersrand plants.)

At the end of the Second World War, very hard, granular activated carbon made from fruit pips was used experimentally for the recovery of gold from slime at the Getchell Mine in Nevada⁹. The fine slime was pumped upwards through a bed of granular carbon retained by a screen, the loaded carbon then being smelted — a costly and wasteful procedure. Acting on a request from the Getchell Mine, Zadra at the United States Bureau of Mines developed a process to elute the gold and silver from this granular loaded carbon. The modified Zadra process¹⁰, which is still in use at the Homestake Mine, used hot caustic cyanide as the eluate. Zadra also developed an electrolytic cell to recover the gold from this eluate. As a result of his work, a pilot plant was operated at Getchell in which loaded granular carbon was eluted chemically and then recycled. (There was no thermal reactivation at that stage.) This chemically eluted carbon maintained reasonable activity for about 10 to 15 cycles.

By 1961, a flowsheet (shown in Fig. 1) had been developed¹¹ in which granular carbon flowing counter-current to the cyanide pulp through adsorption contactors, was used to recover gold. The movement of the carbon in this fashion means that high gold values can be obtained on the loaded carbon from the first contactor, and, because of the presence of 'fresh' carbon in the last contactor, the tailings from the adsorption circuit contain low values of dissolved gold. In this flowsheet, the loaded carbon is eluted by the Zadra process¹⁰ and the gold is recovered electrolytically. An innovation in this flowsheet is the use of thermal reactivation for the chemically eluted carbon before it is recycled. The carbon

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is heated (or reactivated) at about 650°C in the absence of air in an indirectly fired rotary kiln, and immediately attains the activity shown by fresh carbon. This flowsheet has been, and still is, the basis of virtually all the carbon-in-pulp plants developed up to this time. One of the first plants to operate on this flowsheet was the carbon-in-pulp plant at the Carlton Mill at Cripple Creek in Colorado¹¹, which was operating in 1961.

Homestake Gold Mine

The biggest and most important development in the recovery of gold by carbon-in-pulp was the introduction in 1973 of the process at the Homestake Mine^{12, 14}, in South Dakota, where approximately 2250 tons of cyanided slime is treated per day. This carbon-in-pulp plant, which has been operating in a highly successful manner since its inception, has changed the image of the carbon-in-pulp process from an experimental small-scale process into a viable established process that can be used for the treatment of high-tonnage flows.

The Homestake Gold Mine has always had separate treatment processes for its sand and slime fractions. In 1971, when its slime-filtration plant needed to be replaced, a carbon-in-pulp plant was installed. The decision was based on the results of laboratory and pilot-tests carried out at the United States Bureau of Mines at Salt Lake City, and on advice received from the Bureau. The flowsheet of the Homestake plant, which is basically similar to that already described and shown in Fig. 1, is shown in Fig. 2. The process uses granular carbon to adsorb the gold, the carbon being cycled from the adsorption stage to the elution stage, then to the reactivation stage, and finally back to the adsorption stage.

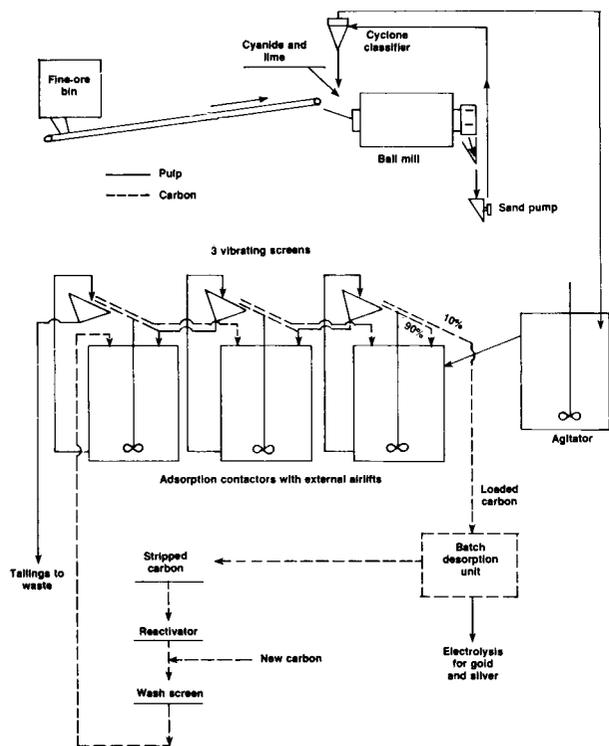


Fig. 1—Typical flowsheet of a carbon-in-pulp circuit for the extraction of gold from cyanided pulp (after Seaton¹¹)

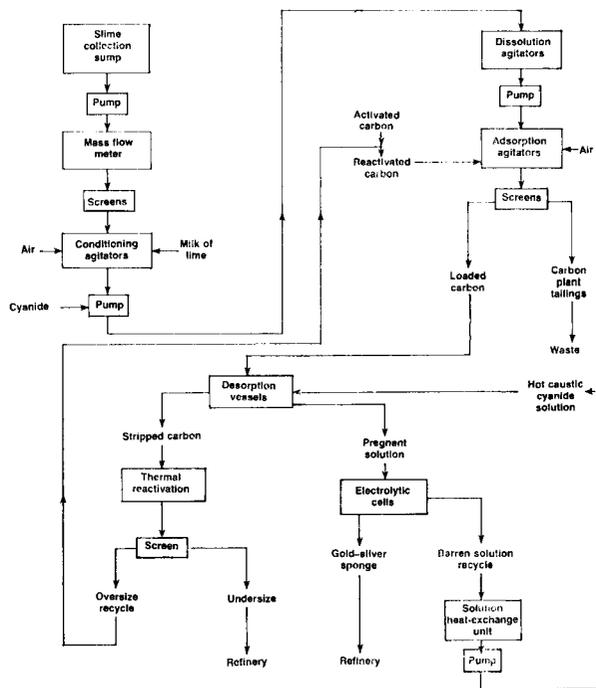


Fig. 2—Flowsheet of Homestake Mining Company's carbon-in-pulp plant for the recovery of gold (after Hall¹²)

Homestake Adsorption Circuit

In the adsorption or recovery section, the dissolved gold is adsorbed onto the carbon. Here it is essential to obtain optimum recovery, i.e. a recovery that will leave in the tailings as little as economically possible of the gold. The flowsheet for the adsorption circuit at Homestake is shown in Fig. 3. The incoming pulp is first screened at 710 μm (24 mesh) for the removal of wood-chips and any oversize material that would otherwise follow the carbon in the subsequent processes. The screened pulp is moved through the adsorption circuit by means of an outside airlift on each adsorption agitator, which raises the pulp plus entrained carbon from each agitator onto an 850 μm (20 mesh) vibrating screen above the agitator. The fine pulp flows through the screen to the next agitator in line, while the coarse, granular carbon is retained on the screen and flows back into the agitator from which it came. The final tailings from the fourth adsorption agitator are screened on a 710 μm (24 mesh) screen to recover the coarsest fraction of any abraded carbon that might otherwise be lost. As the pulp moves through the adsorption stages, the concentration of gold in solution decreases from stage to stage as the carbon adsorbs the gold, i.e. the percentage adsorption increases. On the other hand, the concentration of gold on the carbon, or the carbon loading, increases as it moves countercurrent from stage to stage: loaded carbon is moved once a day at Homestake from the first adsorption stage to elution, equivalent amounts of carbon being moved from stage 2 to stage 1, from stage 3 to stage 2, and from stage 4 to stage 3, while the same amount of fresh or reactivated carbon is added to stage 4. (See Table I for details.)

The following are important factors in an adsorption circuit based on an operation like that at Homestake.

Type of Activated Carbon

Normally, carbon made from coconut shells is used because of its hardness and resistance to abrasion and because of its general availability.

Size of Carbon

The carbon must be sufficiently coarse for it to be separated effectively from the pulp. The finer the carbon granules (i.e. the greater the surface area), the more rapid and more complete is the take-up of gold from solution, and therefore the higher the loadings on the carbon.

Amount of Carbon per Stage

The concentration of carbon in each stage is important with regard to both the rate of adsorption, and the extent of adsorption, of gold in that stage. This concentration of carbon is based largely on the concentration of the dissolved gold.

TABLE I
HOMESTAKE ADSORPTION* CIRCUIT

Stage	1	2	3	4
Carbon concentration†, g/l	18	18	24	24
Gold in solution, g/t	0,72	0,27	0,06	0,015
Head value 1,92 g/t				
Adsorption, %	62,5	85,9	96,9	99,2
Carbon loading†, g/t	11 250	4 500	2 550	600

*The carbon used was between 3,35 and 10 mm (6 to 16 mesh). That now used is between 3,35 and 1,4 mm (between 6 and 12 mesh)

†The total carbon loss was reported to be < 0,1 lb per ton of slime treated, i.e. < 45 g/t.

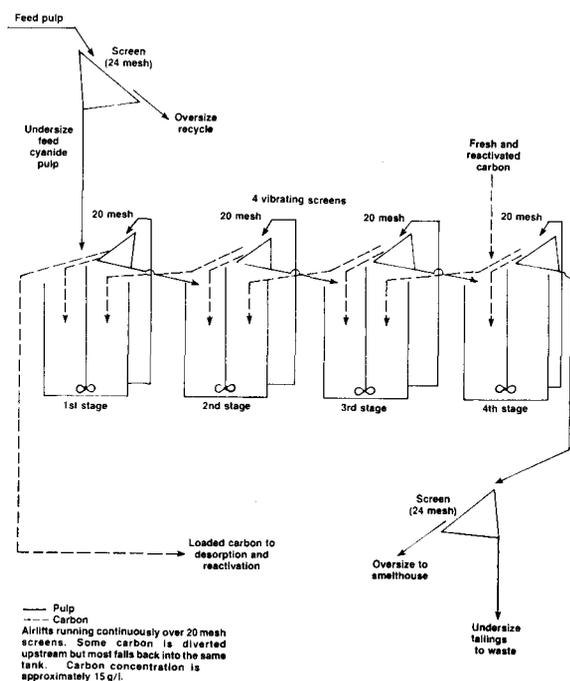


Fig. 3—Carbon-in-pulp adsorption circuit as used at Homestake

Amount of Carbon Moved per Cycle

The amount of carbon moved per cycle (i.e. per hour, per shift, or per day) depends on the amount of dissolved gold fed to the circuit, i.e. its head value, and also on the gold loading on the fully loaded carbon. The latter is usually between 5000 and 10 000 g of gold per ton of carbon, but can be lower or higher (up to 40 000 g/t) than this. If less carbon is moved, the loading on the carbon in each stage is increased, which results in slightly higher values of dissolved gold in each stage.

Number of Stages

The number of stages depends on the head value of the dissolved gold and on the overall percentage adsorption aimed at. Four stages are normally used, but up to seven stages have been employed when pulps with high head values are treated.

Retention Time of Pulp per Stage

Contact times of between 20 and 60 minutes are reported, but contact times of 30 minutes are used frequently.

Amount of Carbon Loss

If the carbon is pumped mechanically with the pulp, it rapidly becomes abraded. For this reason, airlifts are used to move the carbon and the pulp, while eductors (or water pressure) are used to move the carbon. Some carbon is lost in the adsorption circuit due to abrasion, although some of this is recovered on the fine screen at the end of the adsorption circuit. Carbon is also lost as a result of the thermal reactivation, but fine screening after reactivation recovers some of this degraded carbon. Apart from the cost of the carbon lost, there is a cost for the gold associated with, or adsorbed onto, this carbon. Any fine carbon must be smelted so that the gold can be recovered.

Other Metals Adsorbed

The gold in the pulp resulting from normal alkaline cyanidation is adsorbed most strongly of all the metal complexes that are adsorbed by the carbon. Silver is adsorbed rapidly but not as strongly as gold, and nickel is more strongly adsorbed than copper. All the ions compete with one another, and the complexes that are adsorbed vary with changes of pH and ionic strength.

The Homestake Elution Circuit

Hot caustic cyanide (1 per cent NaOH and 0,2 per cent NaCN) is used to elute the gold and silver from the loaded carbon at Homestake, the solution temperature being 88 °C and the elution tanks being conical and made of stainless steel. Upflow elution is used, the hot eluting solution being passed through two adsorption tanks in series before going to electrowinning and back to the first adsorption tank. At Homestake about 50 hours is required to strip the gold from the loaded carbon from about 9000 g/t to less than 150 g/t. This time of elution is said to vary with different ores.

Other Elution Techniques

Other elution techniques that have been reported and are of interest are the following.

Anglo American Technique

In this procedure, which was developed by the Anglo

American Research Laboratories (A.A.R.L.), the loaded carbon is contacted in a cylindrical elution vessel with one bed volume of hot (93°C) 10 per cent NaOH (or NaOH with NaCN) for about 1 to 2 hours, after which it is eluted with hot water, about 7 bed volumes of water being required. This elution procedure may be preceded by treatment with hydrochloric acid, which removes calcium carbonate and most of the base-metal complexes. Homestake does not use an acid-pretreatment step.

*Organic Solvents*¹⁶

The United States Bureau of Mines has reported that elution is more rapid when it is conducted at 80°C with a solution containing 20 per cent methanol, 1 per cent NaOH, and 0,1 per cent NaCN. Although this procedure has yet to be tested on plant scale, the Bureau reports elution times of 6 hours, compared with 50 hours at Homestake, and claims that, when this elution procedure is used, thermal reactivation may be necessary only every 20 cycles.

The Homestake Electrowinning Circuit

The three electrowinning cells, which are used in series, are made of fibreglass. They have stainless-steel anodes and cathodes of steel wool on stainless-steel tubes, the strands of steel wool providing a large surface area for collecting gold. When the cathode in the no. 1 cell contains about 30 kg of gold and 6 kg of silver, it is removed for smelting. Base metals in solution do not present a problem in this electrowinning operation.

The Homestake Reactivation Circuit

Activated carbon can be produced¹⁷ by the heating of a carbonaceous material to a temperature sufficiently high to cause extensive burn-off of the non-carbon impurities, leaving a highly porous product with a high surface area. Oxidation of the surface of the carbon is the most important parameter in activation. If the heating is done in the absence of oxygen, oxidation can occur by exposure of the product to air at any time while it cools.

In the carbon-in-pulp process, the carbon adsorbs traces of impurities, such as iron sulphide, sodium hydroxide, and organic compounds, that are not removed during the elution of gold. The presence of these impurities causes a loss of activity, and thermal reactivation of the carbon is necessary to restore its activity. The carbon is reactivated by being heated in an externally heated rotary kiln at about 650°C for about 30 minutes in the absence of air, and then being allowed to cool in air.

Advantages of Carbon-in-pulp

Because the carbon-in-pulp process eliminates the necessity for filtration and thickening, it has an advantage when applied to any whole ore or fraction of an ore where these two processes present difficulties. These are costly processes with regard to capital and operating costs, and their elimination should result in reduced costs for a carbon-in-pulp plant as compared with a conventional plant. The estimated costs in Table II support this contention.

The carbon-in-pulp process also has an important

TABLE II

COMPARISON OF COSTS FOR CONVENTIONAL AND CARBON-IN-PULP PLANTS

Process	Cost factor	
	Capital	Operating
Conventional countercurrent decantation and Crowe-Merill process	1,00	1,00
Carbon-in-pulp { Potter and Salisbury ¹⁸	0,68	0,77
{ Bhappu and Lewis ¹⁹	0,75	0,94

advantage over the conventional zinc-precipitation process when the ore to be treated contains soluble nickel and copper minerals. These elements can interfere with the zinc precipitation, but do not affect the adsorption of gold by carbon.

The major disadvantage of the carbon-in-pulp process is its requirement that whole ore should be screened at, say, 600 μm (28 mesh) to remove the oversize material. A further possible disadvantage is that gold may be lost to the residue with any fine abraded carbon that is not recovered.

Carbon-in-pulp in South Africa

In South Africa, the first major effort to test the potential of activated carbon for the recovery of gold was made by Rand Mines Limited in the mid-1960s²⁰. The investigations were aimed primarily at the development of an economic method for the extraction of gold from accumulations of contaminated (carbonaceous) materials not amenable to conventional cyanidation techniques.

Tests based on the cyanidation of these materials in the presence of activated carbon showed that the bulk of the gold could be adsorbed by activated carbon, from which the gold could then be recovered by calcination or desorption.

The technical feasibility of the process was proved, but a commercial plant-scale operation was not considered to be economically justified, mainly because there was not a sufficient quantity of relatively high-grade, though contaminated, material in any one locality.

The A.A.R.L. have been actively interested in the use of carbon for the recovery of gold since about 1974, and have conducted tests on its recovery from pregnant solutions and on the recovery of lost gold from waste solutions and residue pulps. The A.A.R.L. have also made a major study of the elution process and have patented²¹ a simplified procedure.

Interest at the National Institute for Metallurgy (NIM) in the carbon-in-pulp process dates from 1974, when it was observed that a flotation concentrate to be produced at the Blyvooruitzicht Gold Mine would probably require fine grinding to liberate the gold. The re-cyanidation and retreatment of this fine material could have posed problems, and the carbon-in-pulp procedure seemed to be suitable for the treatment of this material. An appreciation of the carbon-in-pulp process was obtained from a visit to Homestake in 1975¹⁴, and experimental work using this process was undertaken subsequently.

Laboratory-scale Tests^{22,23}

A simple laboratory procedure was devised to test the performance of the adsorption section of the carbon-in-pulp process, bottles set on rollers being used to represent the stages of an adsorption circuit. Each stage or bottle contained granular carbon and 2 litres of cyanided pulp that had been screened at 600 μm , the concentration of carbon in each stage depending mainly on the concentration of gold. (These concentrations are shown later in the relevant tables.) After a period of contact, usually 1 hour, the pulp in each stage was screened from the carbon and the pulps (without carbon) moved down one stage, a fresh 2-litre sample of pulp coming in at stage 1. The pulp from the last stage, i.e. the final tailings, was filtered, and the filtrate was assayed for gold. A volumetrically measured portion of the carbon in each stage was removed and moved up one stage, fresh carbon being added to the last stage. The carbon removed from the first stage was loaded carbon. The new pulps and carbon in each stage were then mixed and agitated for a further 1-hour cycle.

An important difference between this laboratory-scale procedure and pilot-plant operation is that no short-circuiting occurs in the laboratory tests, whereas it can occur in continuous plant operation. The percentage adsorption in a plant can therefore be lower than that in laboratory tests.

Cyanided pulps from a number of different mines have been tested by this laboratory procedure. Typical results are given in Tables III to XI.

*Blyvooruitzicht Low-grade Circuit*²²

Over 400 cycles or movements of pulp were run in a laboratory carbon-in-pulp adsorption circuit during July and August 1976. The general conditions, which were similar to those at Homestake, were as follows:

Carbon used	Coconut carbon, type PCB of size grading between 3,35 and 1,0 mm (between 6 and 16 mesh)
Number of stages	4
Residence time of pulp per stage	1 hour (i.e. cycle time)
Concentration of carbon	18 g/l in 1st and 2nd stages 24 g/l in 3rd and 4th stages
Pulp in each stage	2000 ml at a liquid/solid ratio of 1
Carbon flow per cycle	2 g (i.e. 4 ml)
Average residence time for carbon	84 hours.

The results (Table III) were consistently high and compared fairly favourably with the gold recoveries obtained by filtration.

TABLE III

TYPICAL ADSORPTION RESULTS AT BLYVOORUITZICHT

Cycle no.	Gold in feed g/t	Gold in final tailings g/t	Adsorption from solution, %
382-385	4,31	0,030	99,3
386-390	3,63	0,023	99,4
391-394	4,44	0,024	99,5

*Flotation Tailings from Sheba Mine*²³

The good adsorption results obtained in the tests at the Blyvooruitzicht Gold Mine led to the request for NIM to undertake similar work on the cyanided pulps of flotation tailings from the Sheba Mine, Barberton. A laboratory-scale test unit similar to that used at Blyvooruitzicht was established at the Sheba Mine, all the general conditions also being similar. Tables IV to VII show typical results obtained in these tests.

TABLE IV

TYPICAL ADSORPTION RESULTS AT SHEBA

Date	Cycle no.	Gold in feed g/t	Gold in tailings g/t	Adsorption %
7 to 10 Jan., 1977	F21-40	3,40	0,010	99,7
17 to 18 Jan., 1977	F73-88	3,33	0,015	99,5
21 to 24 Jan., 1977	F121-136	3,32	0,010	99,7

TABLE V

PROFILE OF STAGE ADSORPTION AT SHEBA

	Head value g/t	Adsorption, g/t			
		Stage 1	Stage 2	Stage 3	Stage 4
Cycle F153	3,320	1,420	0,280	0,115	0,030
Adsorption, %		57,2	91,6	96,5	99,1

TABLE VI

TYPICAL CARBON PROFILES AT SHEBA

Date	Cycle no.	Carbon, g/t			
		Stage 1	Stage 2	Stage 3	Stage 4
13 Jan., 1977	F61	3719	1328	249	67
25 Jan., 1977	R150	4488	1794	1316	173

TABLE VII

TYPICAL ANALYSES OF LOADED CARBON AT SHEBA

Cycle no.	Au, p.p.m.	Ag, p.p.m.	Ca, %	Cu, p.p.m.	Ni, p.p.m.	Si, %
F121-129	4179	247	2,07	601	4871	0,30
F141-149	4241	257	2,35	428	4530	0,40

An interesting feature of the results from the Sheba Mine was that the presence of flotation reagents appeared to have no deleterious effect on the adsorption efficiency.

Durban Roodepoort Deep Mine

In view of the promising results obtained in the laboratory work at Blyvooruitzicht and at Sheba, and because of the interest generated by those results, it was decided that NIM should establish a pilot plant to demonstrate the carbon-in-pulp adsorption process on a suitable and continuous scale. This project was supported by the Chamber of Mines, and the site chosen was the Durban Roodepoort Deep Mine (DRDM); the scale of operations was to be 20 t/d.

Laboratory-scale Carbon-in-pulp Tests on DRDM Ore

Prior to the operation of the pilot plant, laboratory-scale tests were conducted to establish the potential of

the process on this ore. The conditions were similar to those pertaining to the Blyvooruitzicht and Sheba tests, except that only 1 g of carbon per cycle was moved countercurrently. Typical results are shown in Tables VIII to XI.

Pilot Plant at DRDM²⁴

The 20 t/d pilot plant at DRDM was based on the Homestake flowsheet, but only the adsorption circuit was erected. Sufficient new carbon was ordered to serve as feed for the duration of the tests on the plant. The loaded carbon would be returned to DRDM. A flowsheet of the plant is given in Fig. 4.

The feed to this pilot plant was a bleed from the flow of cyanided pulp to the filter plant. This feed was screened at 600 μm (28 mesh), the underflow being pumped to a steady-head tank to feed the adsorption units at a steady rate. To avoid dilution of the feed pulp, no washing was done on the screen. Each of the four stages of adsorption was a mechanically stirred tank

TABLE VIII
AVERAGE RESULTS OF LABORATORY-SCALE TESTS, DRDM

Date	Cycle no.	Gold in feed g/t	Gold in tailings g/t	Adsorption %
21 to 21 Jun., 1977	B49-60	2,08	0,0065	99,7
23 Jun., 1977	B79-90	2,06	0,0100*	99,5*
26 to 27 Jul., 1977	C66-71	2,18	0,0087	99,6
25 Aug., 1977	F36-40	2,31	0,0128	99,4
7 Sep., 1977	G76-83	2,31	0,0111	99,5

*During this cycle the adsorption fell off sharply at one stage. The decrease in adsorption was eventually traced to the resumption of dieselene additions in the main plant: the dieselene coated the carbon and affected the adsorption.

1,22 m in diameter and 1,22 m in height with a volume close to 1300 litres. Two tanks of similar size, one having a slow-speed agitator and the other air-agitation, were sited on the end of the circuit for purposes of comparative testing.

TABLE IX
TYPICAL SOLUTION PROFILES, DRDM

Cycle no.	Head value g/t	Gold in solution, g/t			
		Stage 1	Stage 2	Stage 3	Stage 4
F43	2,308	0,250	0,054	0,031	0,010
Adsorption, %	—	89,2	97,7	98,5	99,6
G87	2,308	0,330	0,070	0,034	0,020
Adsorption, %	—	85,7	97,0	98,5	99,1

TABLE X
TYPICAL CARBON PROFILES, DRDM

Date	Cycle no.	Carbon, g/t			
		Stage 1	Stage 2	Stage 3	Stage 4
21 Jun., 1977	B61	2675	1200	335	68
29 Jun., 1977	B132	4900	1100	200	55
8 Sep., 1977	G87	4725	820	175	60

TABLE XI
TYPICAL ANALYSES* OF LOADED CARBON, DRDM

Cycle	Au p.p.m.	Ag p.p.m.	Ca %	Cu p.p.m.	Fe p.p.m.	Ni p.p.m.	Si %
B50-59	2200	125	0,94	820	220	3450	0,050
B80-89	3050	100	1,00	1080	220	3300	0,046
C64-73	2500	315	1,60	280	250	2900	0,145
F36-45	4300	52	0,68	3100	325	4200	0,110
G76-85	4350	42	0,65	2100	880	1550	0,370

*The variation in the loadings of the different elements shown by these samples is difficult to explain.

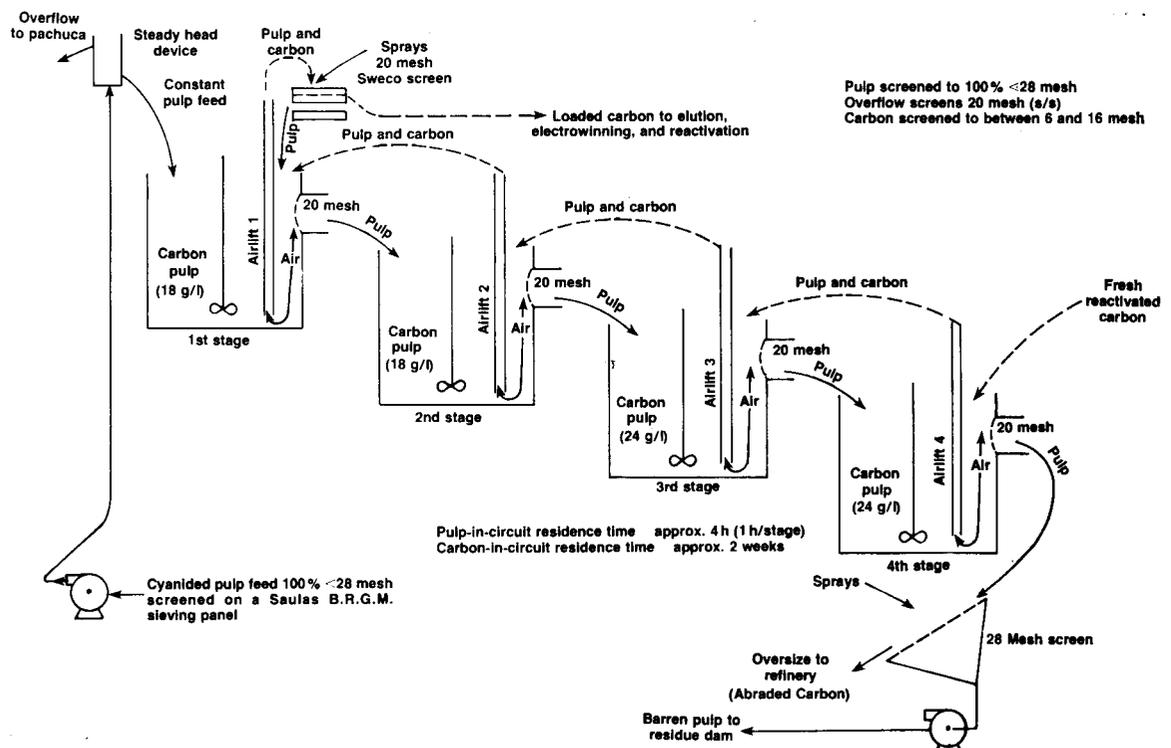


Fig. 4—NIM's modified carbon-in-pulp process

A B.R.G.M. screen, made by Saulus et Cie of France, was used to screen the feed at 600 μm (28 mesh). This screen, which has a nylon screen cloth that can be stored on one spool and wound onto a second spool to expose a fresh screening surface, operated successfully throughout the operating period of the pilot plant. A similar screen was installed after the four adsorption stages to recover a portion of any fine abraded carbon from the tailings.

As described earlier, the pulp and carbon in the Homestake adsorption circuit were moved by being airlifted onto external screens, where the pulp flowed through the screen to the next stage and the carbon flowed back to the same stage. As such continual screening of the carbon could be a cause of attrition, an 850 μm (20 mesh) screen was installed on the pilot plant on the outlet of each adsorption stage to hold back or retain the carbon and to allow the finer pulp through. A stream of air bubbles was blown across it to assist in keeping the screen clear of carbon. (This simple concept was found to operate very successfully, and has since been covered by a provisional patent²⁵.) Airlifts of 5 cm diameter were installed in each adsorption stage to move the carbon countercurrent to the pulp, which meant that the carbon was also moved countercurrent. Because of the flow of pulp and some 'back mixing', there was a temporary increase in the flow of pulp when the carbon was moved.

The carbon-transfer operation took place every 4 hours. The loaded carbon and pulp were airlifted for a fixed time from stage 1 onto a Sweco screen, from where the pulp returned to stage 1. The carbon was then washed, dried, and assayed. To replace the carbon in stage 1, pulp and carbon were airlifted for a similar period from stage 2, and so on along the line, an equivalent amount of fresh carbon being added to stage 4. The volume of carbon in a 10-litre sample of pulp from each stage was measured as a check of whether the circuit remained in balance with regard to the concentration of carbon in each stage. This pilot plant was run continuously for a period of 5 weeks during November and December 1977.

Adsorption, DRDM Pilot Plant

The average results given in Tables XII and XIII illustrate the efficiency of the gold adsorption in the DRDM pilot plant. The conditions on the pilot plant were as follows: at a flow-rate of 20 t/d, the residence time per stage was 1 hour; the carbon concentrations aimed at were 18 g/l in stages 1 and 2, and 24 g/l in stages 3 and 4; and the carbon used, which was SC II coconut carbon supplied by Chemviron, was between 3,35 mm and 1,0 mm (between 6 and 16 mesh).

These results confirmed the consistently good recoveries that can be obtained by the carbon-in-pulp process, which compare favourably with the recoveries obtained by filtration. An advantage associated with these values is their consistency as against the variation in the results obtained with residues from rotary filters due to variations in the efficiency of washing.

Washed-residue Values, DRDM Pilot Plant

The washed-residue values were determined at the beginning of the adsorption circuit. Any decrease in

value through the adsorption circuit could be attributed to the extra dissolution time in the circuit, whereas any increase in value could be attributed to gold associated with fine carbon in the tailings pulp. In the operation of the pilot plant at 20 t/d, there was little or no increase in washed-residue values through the adsorption circuit: there was no extra gold lost on the fine carbon despite the high-speed mechanical agitation, which caused a high degree of carbon abrasion, or this loss was offset by extra dissolution in the adsorption circuit.

Carbon Loading, DRDM Pilot Plant

As shown in Tables XIV and XV, the concentration of each element on the carbon varies with the concentration of the element in the pulp, the concentration of carbon in the stage, and the relative flows of pulp and of carbon.

Recovery of Fine Carbon, DRDM Pilot Plant

Fine carbon was recovered on a 600 μm (28 mesh) Saulus screen at the end of the adsorption circuit of the pilot plant (i.e. after stage 4). The average amount of

TABLE XII
AVERAGE ADSORPTION, DRDM PILOT PLANT

Date	Gold in feed g/t	Gold in solution from 4th stage g/t	Adsorption %
22 Nov., 1977	1,89	0,012	99,4
25 Nov., 1977	2,03	0,018	99,1
28 Nov., 1977	2,14	0,020	99,1
1 Dec., 1977	2,00	0,010	99,5
4 Dec., 1977	1,88	0,016	99,1

TABLE XIII
AVERAGE PERCENTAGE ADSORPTIONS IN EACH STAGE, DRDM PILOT PLANT

Adsorption, %			
Stage 1	Stage 2	Stage 3	Stage 4
60	88	97,3	99,4

TABLE XIV
ANALYSES OF CARBON FROM THE FOUR STAGES, DRDM PILOT PLANT

Element	Stage			
	1	2	3	4
Au, g/t	6648	2941	1010	277
Ag, g/t	630	580	545	405
Ca, %	1,98	1,70	1,55	1,38
Cu, g/t	83	81	97	105
Fe, g/t	475	380	370	360
Ni, g/t	6500	6300	7000	6800
Si, %	0,17	0,18	0,145	0,14

TABLE XV
ANALYSES OF LOADED CARBON ON VARIOUS DAYS, DRDM PILOT PLANT

Element	30 Nov., 1977	3 Dec., 1977	6 Dec., 1977
Au, g/t	6812	6648	6956
Ag, g/t	490	630	427
Ca, %	1,41	1,98	1,08
Cu, g/t	73	83	34
Fe, g/t	380	475	225
Ni, g/t	5200	6500	3833
Si, %	0,146	0,170	0,105

carbon between 20 and 28 mesh collected on this screen was approximately 10 g in 12 hours (i.e. for 10 tons of throughput). This loss is equivalent to 1 g per ton treated. These figures were taken towards the end of the pilot-plant run when most of the carbon in the circuit had been abraded by the mechanical agitators. The assay of a sample of fine carbon is given in Table XVI. The high iron and silicon contents are attributable to rust and slime respectively. In practice, this fine carbon would be smelted for the recovery of its contained values.

Attrition of Carbon, DRDM Pilot Plant

An important factor in the carbon-in-pulp process is the extent to which carbon is lost as a result of attrition by coarse pulp. In the pilot plant, fresh carbon was added to all four adsorption stages at the start of operations. The carbon was fresh and, because of the high-speed mechanical agitators, its volume as measured in each stage decreased for the first two weeks of operation, indicating that it was wearing off. Thereafter, the volumes in all the stages remained virtually constant, which indicated that very little further wear occurred after the initial period. In practice, fresh carbon could be 'pre-conditioned' to abrade off the weak edges of the new carbon granules.

At the end of the pilot-plant run, separate wear tests were conducted in which measured volumes of previously agitated carbon from the pilot-plant run were agitated for 3 weeks with pulp in air-agitated pachuca and in vessels agitated by slow-speed mechanical stirrers. Pulp flowed continuously through these agitated vessels, while the carbon remained in each vessel. When the volume of carbon was measured at the end of this period, the amount of wear appeared to be negligible: approximately 1,3 per cent, or about 0,7 g per ton treated.

Tests at Fairview Mine

The gold ore mined at the Fairview Mine, Barberton, contains arsenopyrite. The ore is milled, and the gold and sulphides are floated into a concentrate, which is roasted. The calcine, which is produced at approximately 20 t/d, has a gold concentration varying from about 150 to 300 g/t, and is treated with cyanide in agitators of the Wallace type. It goes through four stages of agitation, each followed by a decantation stage, before being filtered and washed. The pregnant solutions are clarified and treated by zinc precipitation in the normal way. The zinc-precipitation step can give trouble owing to the presence of nickel and copper in high concentrations and requires a large addition of zinc. In addition, the calcine is difficult to thicken and filter, with the result that the losses of soluble gold to the filter-residue cake can be high. Some of this gold can be recovered in a return-dam solution.

The Fairview pulp therefore seemed to be an ideal

material for the application of the carbon-in-pulp process, and some preliminary laboratory tests showed very good adsorption of gold from the pulp. For the tests on this material, it was decided that an adsorption circuit on the repulped filter residue would permit an assessment of the process that would not be prejudicial to the existing gold circuit. Loaded carbon from this carbon-in-pulp circuit could be brought to NIM for elution and reactivation, the eluate being returned to the mine and added to the normal zinc-precipitation circuit. It was decided that this adsorption circuit should be installed under a project to be partly sponsored by the Chamber of Mines of South Africa.

As the pulp flow at Fairview is the same as that used in the pilot plant at DRDM, tanks of the same size were used in the Fairview pilot plant (1,22 m in diameter and 1,22 m in height). Slow-speed mechanical stirrers were used with an agitation speed of approximately 20 r/min. A gold head value of between 2 and 4 g/t was expected, and four stages of adsorption were decided upon, with carbon concentrations of 18 g/l in stages 1 and 2 and of 24 g/l in stages 3 and 4. The pulp had a residence time of 1 hour in each stage. The carbon used was the eluted and reactivated carbon from the DRDM plant, the flow being 12 litres per day and the carbon being moved once a day.

The circuit was as follows. The filter discharge was repulped, and the pulp was pumped through a 600 μ m (28 mesh) screen to a holding tank, from which the pulp was circulated through a steady-head device to deliver a constant feed to the adsorption section. The overflow from the steady-head device flowed back to the holding tank, while the feed from the steady-head device flowed through the four adsorption stages. Each adsorption stage had an air-cleaned 850 μ m (20 mesh) screen on the overflow to allow the pulp through and to retain the carbon. A safety screen was installed behind each air-cleaned screen before the next stage. The reason for this was that any carbon passing through a hole in the air-cleaned screen would be caught on the safety screen, and steps could be taken to rectify the situation. Each stage had an airlift to move the carbon (and the pulp) counter-current to the flow of the pulp, and there was a Sweco screen on which the loaded carbon from the first stage could be washed.

The plant was sited on a concrete pad, the drainage from which passed through an 850 μ m (20 mesh) screen box set in the pad to collect any spilt carbon. The site was prepared and the various units were installed during April and May 1978, and the plant was ready to run at the beginning of June.

Operating Results from Fairview

Owing to problems associated with the filter unit, the dissolved gold in the feed to the carbon-in-pulp plant at Fairview during the month of June was very much higher than the expected feed of 2 to 4 g/t. The carbon concentrations were increased to 24 g/l in stages 1 and 2, and to 32 g/l in stages 3 and 4, to cope with this higher concentration of gold.

Table XVII summarizes the results for the first month of operation at Fairview. This carbon-in-pulp plant recovered over 6 kg of gold in its first month of operation.

TABLE XVI

ASSAY OF A SAMPLE OF FINE CARBON, DRDM PILOT PLANT

Au g/t	Ag g/t	Ca %	Cu g/t	Fe g/t	Ni g/t	Si %
551	44	0,27	< 20	≈ 8700	1260	≈ 3,6

As there were only four adsorption stages and there was insufficient carbon to handle the unexpectedly high gold content, the average gold concentration in the barren solution from the plant was 0,19 g/t.

The operation of this plant for one month was most successful, demonstrating that, for this Fairview

TABLE XVII

SUMMARY OF JUNE OPERATING RESULTS, FAIRVIEW

Solids fed to plant, t	436
Solution fed to plant, t	657
Average gold in solution, g/t	9,62
Average gold in barren solution (stage 4), g/t	0,19
Average overall adsorption, %	98,0
Dissolved gold to circuit, g	6317
Dissolved gold from circuit, g	124
Dissolved gold recovered, g	6193
Loaded carbon removed from circuit, kg	294

TABLE XVIII

AVERAGE MONTHLY SOLUTION PROFILE, FAIRVIEW

Feed g/t	Gold in solution, g/t			
	Stage 1	Stage 2	Stage 3	Stage 4
9,62	5,22 (45,7%)*	1,91 (80,1%)	0,41 (95,7%)	0,19 (98,0%)

*The adsorption in stage 1 varied between 19 and 74 per cent, depending mainly on the concentration of gold in the feed, which, in turn, affected the value on the loaded carbon.

TABLE XIX

AVERAGE MONTHLY ANALYSES OF LOADED CARBON, FAIRVIEW

Au p.p.m.	Ag p.p.m.	Ca %	Cu p.p.m.	Fe p.p.m.	Ni p.p.m.	Si p.p.m.
18 282	402	2,13	523	2614	16 149	1501

TABLE XX

TYPICAL AVERAGE ADSORPTIONS, FAIRVIEW

Cycle no.	Head value g/t	Gold in tailings solution g/t	Extraction %	Carbon loading g/t
A41-48	164,3	0,015	99,991	13 500
B105-112	102,2	0,013	99,987	15 900
C33-40	95,1	0,020	99,979	9 600
E33-40	154,1	0,035	99,977	37 900

TABLE XXI

TYPICAL AVERAGE SOLUTION PROFILES, FAIRVIEW

Cycle no.	Gold in solution, g/t				
	Head	Stage 1	Stage 2	Stage 5	Stage 7
A52-84	155,1	19,8	1,60	0,80	0,040
B21-53	112,1	18,1	1,50	0,40	0,044
C56-88	81,3	18,0	0,70	0,10	0,032
E9-32	153,0	46,9	6,40	3,90	0,034

TABLE XXII

TYPICAL CARBON PROFILES, FAIRVIEW

Cycle no.	Carbon, g/t						
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
A126	12 400	2 250	765	423	385	334	338
B126	15 700	4 150	1 980	825	450	340	355
C126	6 700	2 900	1 200	380	330	330	240
E125	25 500	7 900	2 400	1 390	1 170	1 150	1 190

material, the carbon-in-pulp process can yield gold recoveries very much higher than those that can be obtained by the normal filtration process (see Tables XVIII and XIX).

Elution and Reactivation of Carbon, Fairview

In the initial stages, elution and reactivation were carried out rapidly to provide carbon for recycling, and no valid results are available.

Laboratory-scale Tests, Fairview

The aim at Fairview is the eventual treatment of the high-grade calcine pulp by carbon-in-pulp, with elution and reactivation of the carbon and electrowinning of the gold in the eluate.

The parameters necessary for effective adsorption were determined in a series of laboratory-scale runs conducted on the calcine pulp. Over a 5-week period, tests were conducted in seven stages with 2 litres of pulp per stage and cycles of 1 hour. The following four sets of conditions were tested:

Sequence A 48 g of carbon per litre of pulp in all stages and moving of 20 g of carbon per cycle.

Sequence B 48 g/l in all stages and moving of 14 g of carbon per cycle

Sequence C 24 g/l in all stages and moving of 20 g of carbon per cycle

Sequence E 24 g/l in all stages and moving of 7 g of carbon per cycle.

The results are given in Tables XX to XXIII.

From the results given in Table XXIV, it can be seen that the adsorption of nickel by carbon under these conditions is almost complete.

Probable Future Work, Fairview

The very efficient adsorptions obtained in the laboratory-scale circuits and the highly satisfactory operation of the present four-stage 'scavenger' circuit at Fairview have shown that it is feasible to continue with the design of a fully integrated carbon-in-pulp circuit for the Fairview calcine.

The adsorption conditions employed in sequence E seem to be the best. With seven adsorption stages of 1200 litres each, the total pulp residence time will be 7 hours (i.e. 1 hour per stage), while the average carbon residence time in the adsorption circuit will be approximately 60 hours. It will be necessary for the carbon to be airlifted countercurrent to the flow of pulp at frequent intervals, or perhaps even continuously, because of the short residence time of the carbon in each adsorption stage as a result of the high concentration of dissolved gold to be extracted. As a preliminary step, it is intended to operate a seven-stage adsorption circuit with these carbon concentrations and carbon flow-rates on the present filter-residue pulp to demonstrate that it is practicable for the

required distribution of carbon to be maintained in all stages. An elution column and a regeneration kiln are being planned, the designs of which are based partly on the tests done to date at NIM and partly on other experience. In addition, an electrowinning circuit is being designed that will combine the experience gained at the A.A.R.L., NIM, and Homestake.

Larger-scale Developments

A fairly large-scale fully integrated plant is required to effectively demonstrate the carbon-in-pulp process on Witwatersrand ores and to supply valid cost and design data for the process. A private operator has erected a new plant to treat a combination of fines from a crusher plant and reclaimed material from old sand dumps and rock dumps at a rate of 250 tons per day. NIM and A.A.R.L.²⁶ assisted in the design and helped in the start-up of a plant to recover gold from this material by the carbon-in-pulp process. The experience on which the design and operation of this plant are based was obtained in the pilot plants at DRDM and Vaal Reefs²⁷. In return for the assistance from NIM and A.A.R.L., the plant operator agreed that all the operating results would be made available to the gold-mining industry through NIM. The

new plant (Fig. 5) includes adsorption, elution, reactivation, and electrowinning stages.

Other Applications in Gold Recovery

As mentioned earlier, fine carbon can be added to a cyanided pulp to adsorb gold, and the fine carbon can then be floated off and smelted. Tests have been conducted for some time along these lines, particularly on repulped filter residues. The following results²⁸ were obtained in a recent plant-scale test in which fine carbon was added to a repulped cyanidation residue before it was sent to a flotation plant for the recovery of pyrite:

Dissolved gold in feed, g/t	0,16
Dissolved gold in barren solution, g/t	0,016
Carbon added per ton of ore, g	16 to 50
Gold loaded on carbon, g/t	3000 to 8000
Approximate recovery, %	90
Estimated improvement in calcine grade, g/t	3,5 to 7,0

Summary

The use of activated carbon for the recovery of gold from cyanide solutions dates back to 1894. Until the development of an efficient procedure for stripping the

TABLE XXIII
TYPICAL ANALYSES* OF LOADED CARBON, FAIRVIEW

Cycle no.	Au p.p.m.	Ag p.p.m.	Ca %	Cu p.p.m.	Fe p.p.m.	Ni p.p.m.	Si p.p.m.
A110-117	12 600	119	0,97	10 100	1 500	1 470	1 840
B126	15 700	369	1,76	4 265	2 580	12 050	1 885
C77-84	7 950	224	1,33	1 360	1 950	11 600	2 750
E125	25 500	820	2,23	710	2 430	17 100	630

*The fluctuations in the adsorption of the various elements cannot be explained.

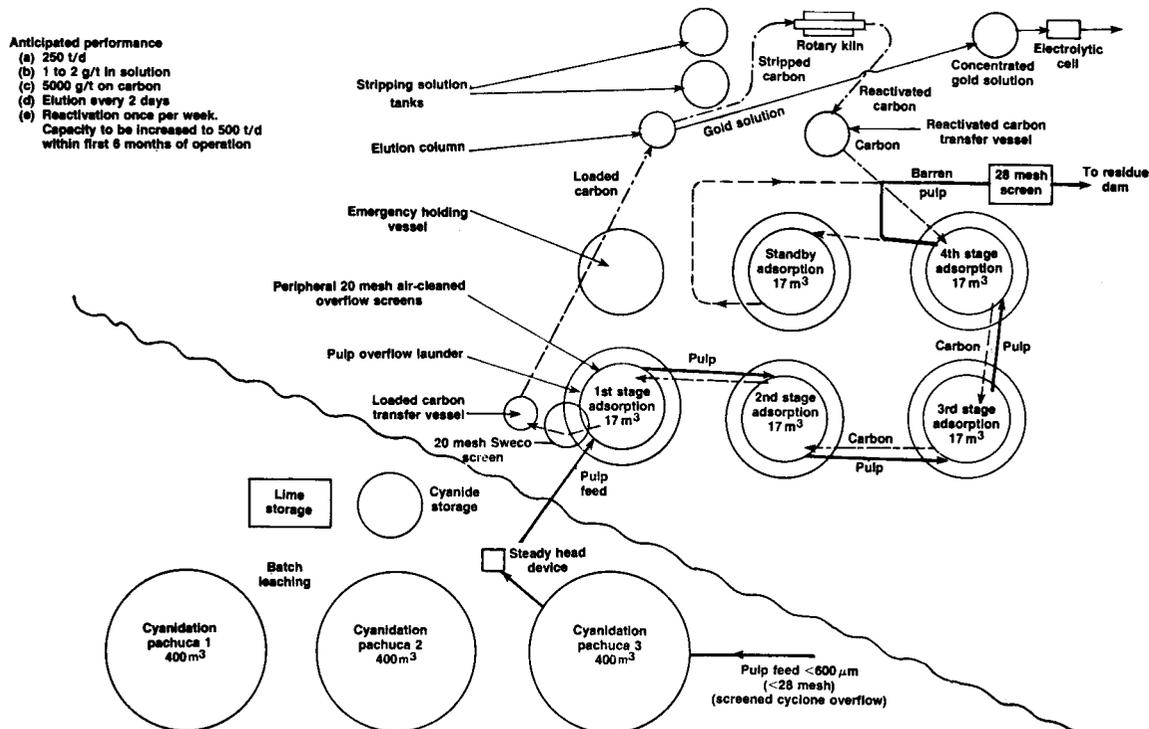


Fig. 5—Sketch of the layout of the new plant

adsorbed gold from the loaded carbon, the gold was recovered by smelting the carbon. A carbon-in-pulp system involving chemical elution of the loaded carbon, an electrowinning system for recovering the gold from the eluate, and thermal reactivation of the eluted carbon was developed by the United States Bureau of Mines.

The capital and operating costs of the carbon-in-pulp process are claimed to be lower than those of the conventional process. The Homestake Mine has operated economically and successfully since 1973 on a carbon-in-pulp system treating slimes at the rate of 2250 t/d. This record indicates that the system should now be regarded as a fully proven and established process. From a feed pulp in which the dissolved gold was 1,92 g/t, the carbon-in-pulp process produced tailings with a gold concentration of 0,015 g/t, representing a direct recovery of 99,2 per cent of the dissolved gold.

A number of South African gold pulps were tested in laboratory-scale carbon-in-pulp tests, the Homestake type of process being used, i.e. four adsorption stages containing carbon flowing countercurrent to the pulp. Typical recoveries from these pulps are given in Table XXV.

Based on these results, a pilot plant having a capacity of 20 t/d was erected at the Durban Roodepoort Deep Mine to test the adsorption circuit of a carbon-in-pulp process. A novel improvement to retain the carbon in an adsorption tank was devised and patented, and the circuit operated continuously for about five weeks, yielding satisfactory results. The following typical results were obtained:

Dissolved gold in feed pulp	Dissolved gold in tailing pulp	Adsorption %
g/t	g/t	%
1,89	0,012	99,4
2,14	0,020	99,1

A plant with a capacity of 20 t/d has been installed at Fairview Mine to recover gold from the filter tailings of the calcine pulp. This plant has operated satisfactorily since the beginning of June 1978. A fully integrated carbon-in-pulp plant will most probably be installed at Fairview in the near future to treat their initial calcine pulp, which has a gold head value of over 150 g/t.

TABLE XXIV
NICKEL VALUES IN SOLUTION

Cycle no.	Feed to adsorption circuit p.p.m.	Tailings from adsorption circuit p.p.m.	Adsorption %
B34	129	2	98,4
B55	132	3	97,7
C7	104	2	98,1

TABLE XXV

TYPICAL RECOVERIES FROM VARIOUS SOUTH AFRICAN GOLD PULPS

Mine	Gold head value g/t	Gold in final tailing g/t	Adsorption %
Blyvooruitzicht	3,63	0,023	99,4
Sheba	3,33	0,015	99,5
Durban Roodepoort Deep	2,31	0,011	99,5

Laboratory-scale tests using a seven-stage adsorption circuit have given the following results on Fairview pulp:

Dissolved gold in feed pulp	Dissolved gold in tailing pulp	Adsorption %
g/t	g/t	%
154,1	0,035	99,98

A fully integrated carbon-in-pulp plant to treat about 250 t/d has been erected for a private operator. The capital and operating costs of this plant are being made available to the gold-mining industry.

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Viscosities, electrical resistivities, and liquidus temperatures of slags in the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-TiO}_2\text{-SiO}_2$ under reducing conditions

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SYNOPSIS

Selected members of the slag system were reduced in graphite crucibles in an argon atmosphere, and the physico-chemical properties of the reduced derivatives of the slags were determined in inert crucibles.

It was found that slags having magnesium aluminium titanate as the primary phase before reduction underwent an increase in liquidus temperature, accompanied by a change in the primary phase. No analogous behaviour could be detected for the slags having perovskite as the initial primary crystallization product. In most instances, the viscosity of the melt passed through an initial minimum, followed by an increase as the reduction time was extended. Increased MgO/CaO ratio, basicity, titania content, and reduction temperature all served to accelerate thickening. During reduction, the electrical conductivity of the slags tended to rise relative to the value for the unreduced melt.

SAMEVATTING

Geselekteerde slaksamestellings is met koolstof gereduseer in 'n argon atmosfeer. Die fisiko-chemiese eienskappe van die gereduseerde slakke is daarna bepaal in onaktiewe kroesies.

Dit is vasgestel dat slakke wat magnesium aluminium titanaat voor reduksie as primêre fase gehad het, gedurende reduksie 'n smeltpuntverhoging ondergaan wat teweeggebring word deur 'n verandering van die primêre fase. Slakke wat aanvanklik perovskiet as primêre fase het, ondergaan nie sodanige verandering nie. In die meeste gevalle gaan die viskositeit van die slak aanvanklik deur 'n minimum, maar by verdere reduksie verdik dit. Verdikking word verhaas deur 'n verhoogde MgO/CaO verhouding, basisiteit, titaanhoud en reduksietemperatuur. Die elektriese geleidingsvermoë van die slakke was geneig om te vermeerder gedurende reduksie.

Introduction

In an earlier paper¹ it was shown that the slags in the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-TiO}_2\text{-SiO}_2$ are very fluid under neutral conditions. However, because practical difficulties are experienced during the smelting of titaniferous burdens, it was necessary to determine the physico-chemical properties of these slags under the reducing conditions existing in a furnace.

The effect of reducing conditions on the viscosity of titaniferous slags has been the subject of many investigations²⁻¹⁰. While it is generally agreed that the reduction of titanium oxide is at the root of the problems, which are variously described as high viscosity, accretion formation, and difficult tapping, some controversy remains over the mechanism affecting furnace operation.

It is possible that oxygen loss from a slag to a degree corresponding to the existence of lower oxides of titanium can influence the viscosity. More recent investigations have proved that such conditions can increase the liquidus temperatures of slags⁸⁻¹⁰, which partly explains thickening under reducing conditions at a constant temperature as reported earlier^{2, 3}. Handfield *et al.*¹⁰ made additions of titanium oxides to a $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ slag, and found that TiO and Ti_2O_3 increased the liquidus temperature substantially after a slight decrease at low concentrations of the oxides. On the basis of the activation energy for viscous flow, they

found Ti_2O_3 to be a better network modifier than either TiO or TiO_2 . Gruzdev *et al.*⁹ actually linked the changes in liquidus temperature with accompanying changes in primary phase, but their results appear to prove the opposite of those of Handfield *et al.*¹⁰ with respect to the relative effects of TiO_2 and Ti_2O_3 upon viscosity.

Ohno and Ross⁵ measured the viscosity of slags in the system $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-TiO}_2$ continuously and isothermally while the slags were contained in graphite crucibles in an argon atmosphere. The technique would considerably mask the appearance of a new more-refractory phase, but the authors did mention the possibility to explain the very rapid increase in the viscosity of a 50 per cent TiO_2 slag at temperatures up to 1550°C, as compared with the more gradual thickening of the same slag at 1600°C. It was also shown that increased temperature, a higher alumina content, and replacement of the argon with nitrogen in the furnace atmosphere all increased the thickening rate, and that carbon as the reductant was a prerequisite for thickening. The viscosity did not increase when CO was the reducing agent.

An alternative thickening mechanism could be that causing the appearance of finely dispersed reaction products consisting of titanium carbide, nitride, or a solid solution of these. Ohno and Ross⁵ discarded the suggestion since these solid phases could be expected to form surface layers. Semik³, working on blast-furnace type slags, found that sufficient carbide was formed after prolonged reduction in graphite crucibles to cause marked thickening. Freidenzon⁶ attributed the change in viscosity occurring in members of the system $\text{CaO-SiO}_2\text{-}$

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