Obtaining Metallurgical Data from Drill Core Samples Using a Mini Pilot Plant

V L L Andrade, N A Santos, K L C Gonçalves,
Companhıa Vale Do Rio Dote Mineral Development Center BR262 km 296 Santa Luzia MG, Brasil

H Wyslouzü, G Dâvıla,
Canadian Process Technologies Ine Unit 1 7168 Honeyman Street Delta British Columbia Canada V4G 1G1

ABSTRACT :When confronted with the difficult decisions on advancing an exploration project to the feasibility and construction stages, it is important to know how various regions of the ore body will react in the milling and concentration processes While bench scale test work is common and inexpensive, the results and information provided are somewhat limited due to the difficulty in accurately predicting the effects of recirculating middling streams or gradual changes in solution chemistry

Conventional Pilot Plants, processing 100 to 1,000 kg/hour of sample ore, provide the detailed engineering data required to develop a final process flowsheet and to size the equipment They are, however, expensive to set up and operate, and are really only viable for major projects that are well advanced

In the latter part of 1999, the Mineral Development Center at CVRD (MDC) purchased a new piece of mineral processing equipment which can run continuous flotation tests using drill core samples To evaluate its performance, and to compare it with conventional testing methods, various types of flotation tests were carried out using two different types of copper ore The limitations and advantages of open circuit and locked cycle bench tests, as well as the Mini Pilot Plant and the Conventional Pilot Plant were evaluated

Open circuit tests carried out at the bench scale only provide basic information More complete and trustworthy information is obtained, m terms of the recirculation of flows and reaching a permanent and stable flotation regime as the dynamics and complexity of the tests increases The data obtained showed that the MPP's metallurgical performance was equivalent to that of a conventional pilot plant

1. INTRODUCTION

The future of the mining industry lies in its ability to find and develop new mineral deposits According to figures published by the Mining Association of Canada, more than $US2 34 Billion was budgeted for exploration in 2000 by some 656 mining companies operating worldwide In Canada alone, over $500 million was spent on exploration and deposit appraisal during this period

The proper evaluation of a new mineral deposit is a complex and involved process requiring input from many disciplines including exploration geologists, mining engineers, mineral processors, economists and marketing specialists The mineral processing engineer is a key member of the team, for it is he who has the task of finding a treatment process that is both economical and robust enough to handle the expected variations in ore types Capital and operating costs are very sensitive to the process selected Over the years, many projects have failed due to high operating costs resulting from unexpected metallurgical responses to mill feed ore blends A better understanding of the nature and variability of the deposit means a lower risk for the investor

When confronted with the difficult decisions on advancing an exploration project to the feasibility and construction stages it has always been the dream of process engineers to know, with greater certainty, how various regions of the ore body will react in the milling and concentration processes While bench scale test work is common and inexpensive, the results and information provided are somewhat limited due to the difficulty in accurately predicting the effects of recirculating middling streams or gradual changes m solution chemistry

Conventional Pilot Plants, processing 100 to 1 000 kg/hour of sample ore, are used to provide the detailed engineering data required to develop a final process flowsheet and to size equipment They are, however, expensive to set-up and operate, and are really only viable for major projects that are well advanced Typical sample and manpower requirements for different testing options are compared in Table 1

Table 1 Comparison of Testing Methods

	Bench	Mini Pilot Plant	Conventional Pilot
Amount of ore	1-4 kg per test	5-15 kg/h	100 - 1000 kg/h
Origin of the ore	Drill core	Drill core	Underground gallery
Cost of the ore	Included in exploration costs	Included in exploration costs	- $US 500,000 - 2 million
Cost of operation and analyses	- $US 150 00 per test	- $US 6,500 per 20 hr test	- $US 10 - 20,000 per 20 hr test
Personnel	I technician and 1 assistant	1 technicians and 1 to 2 assistants per shift	I to 2 technicians and 4 assistants per shift
Attained Information	. Ore characteristics • Stages and kinetics of flotation, reagents, reagent dosages	• Mass balances • Metallurgical & water balances • Detailed engineering information	• Mass balances • Metallurgical & water balances • Detailed engineering information
Limitations	Does not allow evaluation of continuous flows	Produces small quantities of concentrates	Expensive, demands much ore generates great mass of tailings
Advantages	Simple and inexpensive	ᶜ Allows evaluation of continuous streams with a small amount of ore ª Is operationally inexpensive and allows ore evaluation from different regions of the deposit » Is much more environmentally friendly	° Provides reliable data for industrial scale-up ° Can generate large concentrate samples for smelter tests

The process development for new projects involving flotation normally consists of bench scale studies followed by pilot plant testing and subsequent scale up to the industrial plant The bench scale studies permit determination of basic parameters for the process These parameters include such items as mmeralogical and liberation characteristics, a preliminary treatment flowsheets, flotation kinetics, reagent types and dosages, etc The studies are also used to estimate the variability of the ore body by testing samples of different hthologies obtained from different zones within the deposit The preliminary flotation tests are usually done using drill core samples obtained from the exploration program as these tests require small amounts of sample, usually from 1 to 4 kg of ore Operationally, they are simple and inexpensive tests, and they are usually carried out in open circuit

To obtain a preliminary estimation of recirculating loads, it is possible to conduct locked cycle tests which are of greater complexity but provide more detailed information Locked cycle tests can produce good results for simple ores Knowing when steady state has been reached, however, and being able to interpret the results correctly, is not always an easy task (Ounpuu, 2000) In general, the principle limitation of bench scale testing is its inability to replicate the mixing regimes and process conditions of a continuous closed circuit operation

To evaluate the process on a continuous basis, pilot scale tests are performed which allow mass, metallurgical and water balances to be obtained along with more detailed information for the project engineering studies These tests are expensive and demand considerable operational effort Continuous pilot plants also consume great quantities of ore, ranging between 100 and 1,000 kg/h per test As these tests are conducted during the feasibility phase of the project, it is often necessary to develop an underground adit exclusively for obtaining the bulk ore samples, making the investment in terms of cash outlay and project schedule even greater

In 1999, the Mineral Development Center at CVRD purchased new laboratory equipment referred to as the Mini Pilot Plant (MPP), designed and fabncated by Canadian Process Technologies (CPT) This equipment, originally developed at Commco's research center at Trail, is designed to allow flotation testing with continuous flows, similar to a traditional pilot plant, but operating with a minimum amount of ore and personnel. A major part of Cominco's original justification was to reduce the need to conduct locked cycle tests. The Mini Pilot Plant developed by CPT was specifically designed to make use of the samples obtained from exploration drilling campaigns. The MPP is the first equipment of its type to be used in Brazil and has proven very useful in the evaluation of flotation processes.

This paper presents comparative tests results for three types of flotation studies: bench scale tests, locked cycle tests and continuous flow tests making use of the MPP as well as a larger conventional pilot plant. Two copper ores of varying complexity were used for this comparative test work.

2. DEVELOPMENT OF MINI PILOT PLANT (MPP)

As outlined earlier, the benefits of conducting continuous closed circuit tests using small sample quantities are numerous. There are certain challenges, however, when working with very low flow rates. The basic philosophy and design criteria for the equipment can be summarized as follows:

- The scale of the equipment should be convenient to handle feed rates ranging from 5 to 15 kg/h.
- Grinding should be done in batches of 30 to 50 kg as continuous grinding / classification at this scale would be too difficult to control.
- The circuit should be arranged to permit maximum flexibility for circuit configuration.
- The flotation cells should be modeled after standard laboratory flotation cells and use the same impeller and tank design to eliminate cell design as a variable.
- The unit should use a high level of instrumentation to permit replication of conditions from test to test. Instrumentation should include digital air flow measurement, pH / eH measurement, precision reagent addition, variable speed froth paddles, impeller speed measurement and variable speed slurry transfer pumps.
- It should include ancillary equipment such as a continuous regrind mill and a miniature flotation column to permit testing of common industrial circuits.

The MPP comprises 12 flotation cells, each of 1.7 L capacity. The cells were modeled after the Denver D12 laboratory flotation machine and use the same impeller and stator design. The shape of the tank is also the same as the Denver cell but includes an adjustable level control system. Concentrates and tailings are transferred from cell to cell with small peristaltic pumps. A wide variety of flotation circuits can be reproduced in the MPP, including the most common combinations of rougher, scavenger and cleaning stages. The equipment acquired by CVRD includes a pin mill for the continuous regrinding of intermediate concentrates.

The following photographs show some of the individual components and the final assembly.

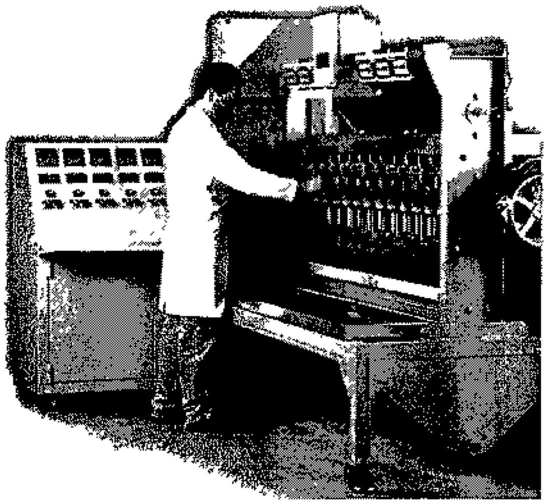

Figure 1 : Overview of Flotation Module and Control Panel

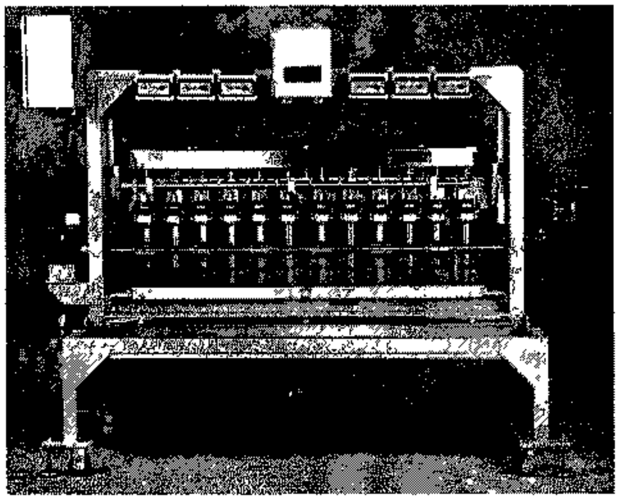

Figure 2   Front View Showing Pump Controllers and Air Flowmeters

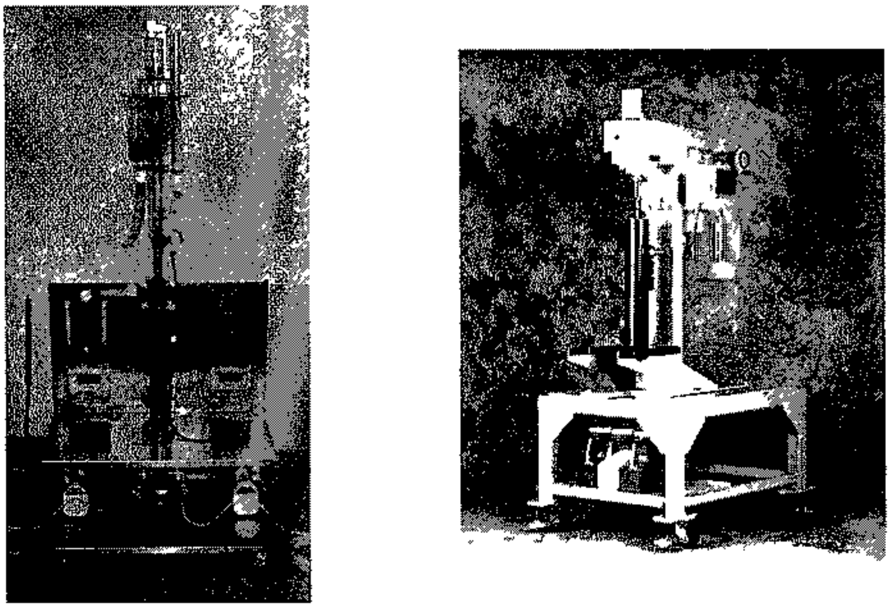

Figure 3   Column Cell Module and Regnnd Module

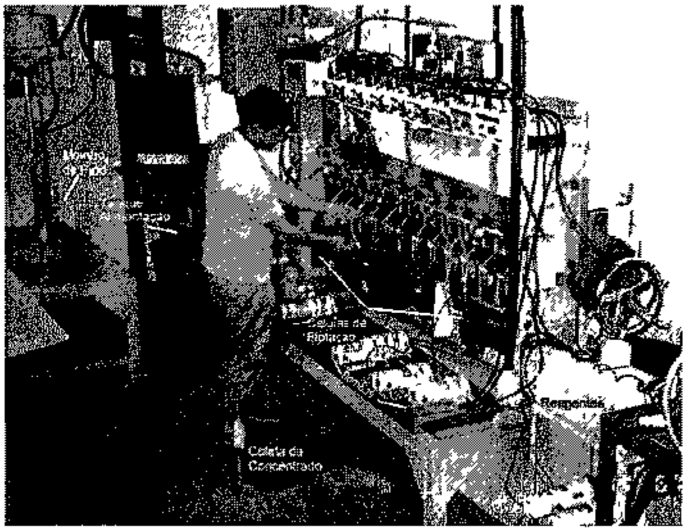

Figure 4 Mini Pilot Plant m Operation

3. TEST PROGRAM

Test Samples

Two different copper ores originating from the northern region of Brazil were selected for testing and evaluation. These samples were designated as Ore A and Ore B. Ore A is a mixture of bornite and chalcocite, with a very fine grain structure (P =16 fim). Ore B is primarily chalcopyrite and has a coarser grain size (P = 44 jwn).

Process Description

The ores were subjected to the following treatment stages:

- Grinding
- Rougher and Scavenger flotation
- Regnnding of the combined Rougher and Scavenger concentrates
- Cleaning of the «ground product (cleaner 1)
- Scavenging of the cleaner 1 tailings
- Recleaning of the concentrate (cleaner 2)

Figure 5 shows the basic flowsheet used in the tests.

For Ore A, two different flowsheets were tested to enable production of both a low grade concentrate (25% Cu) and a high grade concentrate (38% Cu). The flowsheet shown in Figure 5 was used to produce the low grade concentrate. Two additional cleaning stages were added in order to produce the high grade concentrate. This test (high grade) was compared with a previous conventional pilot plant test campaign.

Bench Scale Tests

Bench scale flotation testing was performed m a Denver D12 laboratory cell with self aeration and rotational speeds of 900 and 1500 rpm depending on the flotation stage. The grinding was carried out m a ceramic mill using steel rods and the regrinding was carried out using a ceramic mill and steel grinding balls.

In order to determine the conditions to be used in the locked cycle tests and in the continuous flow test, bench scale testing was carried out only up to the first cleaner with a timed collection of products during the stage.

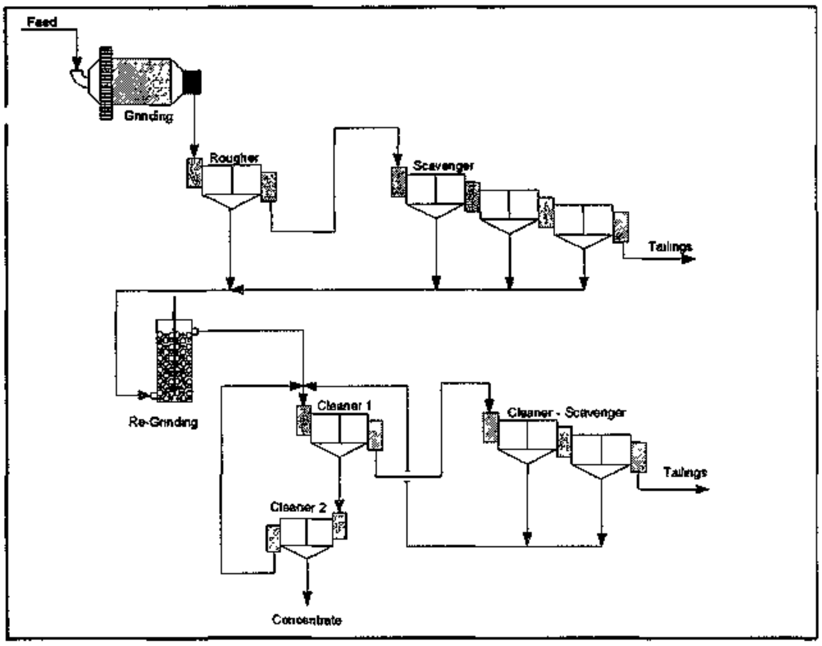

Figure 5: Simplified flowsheet for processing of Ores A and B

Locked Cycle Test (LCT)

In a continuous process, the concentrate of the cleaner scavenger and the tailings of second cleaner are recirculated to the feed of the first cleaner. In order to simulate this process as a series of bench scale tests, the tests are carried out in a closed circuit or "locked cycle" (LCT) test. An LCT comprises a sequence of flotation tests in which the intermediate products of a test cycle are added to the appropriate stage of the subsequent cycle. Therefore, the recirculation of the cleaner scavenger concentrate to the first cleaner is carried out by the addition of the cleaner scavenger concentrate from test (n-1) to the feed of the cleaner test (n). The test series is terminated when the circuit is stabilized, as verified by the mass and grade of the final products, which must remain constant between successive cycles, and the balance must match the initial sample data.

Mini Pilot Plant (MPP)

The initial grinding was carried out separately in 20 kg batches using a rod mill. The ground product was transferred to an agitated holding tank and then to the MPP feed tank. Feed slurry was pumped to the Mini Pilot Plant using a peristaltic pump.

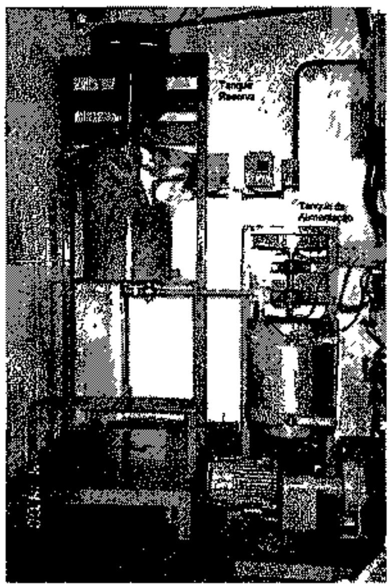

Figure 6: MPP feed system showing holding tank (L) and feed tank (R)

Tests were performed at a continuous feed rate of 5 kg/h using the circuit configuration shown in Figure 7

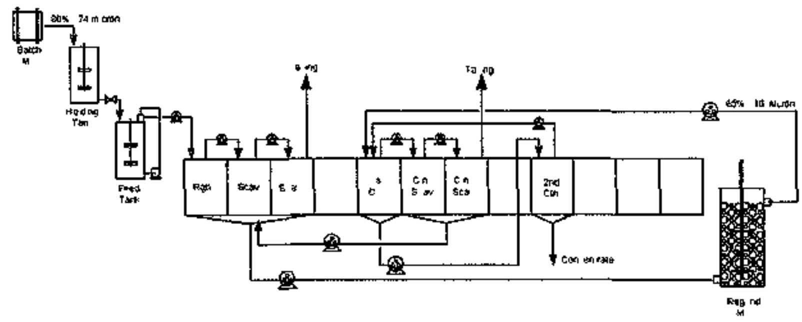

Figure 7 MPP Circuit Configuration

Conventional Pilot Plant

The grinding and flotation pilot plant circuits available at the CDM have a maximum capacity of *500* kg/h The giindmg section includes a variable speed transfer system and a primary ball mill operating m closed cucuit with a spiral classıfıeı The flotation section is very flexible m teıms of quantity of mechanical cells Cells of 25, 50, 60, 150 and 500 liters are available

Ore type B was extensively tested in the pilot plant in the past The results obtained by the MPP were compared to the results obtained from the conventional pilot plant

4. RESULTS

Preliminary Tests

It was necessary to conduct a series of pıelımınary tests to establish basic operating conditions and characteristics for the MPP Specific tests weie performed to evaluate the performance of the Rougher and Scavenger stages Figure 8 shows a photogiaph of these stages

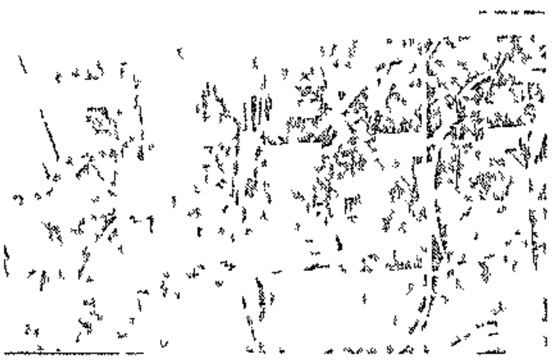

Figure 8 Rougher (1 to the left) and Scavenger Cells (2 and 3 to the light)

To evaluate these stages, a series of bench scale and Mini Pilot Plant tests was perfoimed The bench scale tests were done in a 2,500 mL Denver D12 flotation machine operating at 1,200 rpm The pioducts were collected in stages and timed accordingly In the Mini pilot Plant, 3 flotation cells were used, the first operating as a ıougher and the other two opeıatıng as scavengeis Flotation conditions such as the percent solids and ıeagent addition ıates were kept the same for both tests Figure 9 shows the results of copper grade and lecovery achieved in the bench scale test as well as from the Mini Pilot Plant

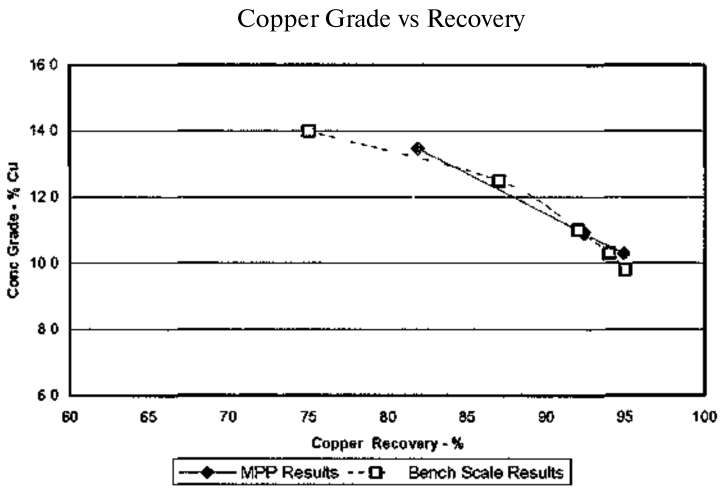

Figure 9 Copper Grade/Recovery Curves for the Bench and Mini Pilot Plant Tests

The results obtained from both tests were very similar, demonstrating that the values obtained from the standard bench scale test can be reproduced in the Mim Pilot Plant Figure 10 shows the mass, water and copper balances obtained from the Mini Pilot Plant test

This general balance was generated using software called Bilmat, and it shows that the calculated values have a very small deviation relative to the measured data Most of the tailings values deviated by less than 3 % with a maximum deviation of 7 5%, indicating that the process had stabilized prior to sampling

Figure 11 shows some modifications which were done to the MPP to make operation easier The white circles indicate the feeding system into each cell The hose on the left cell is supported only by a tube which feeds the material to the bottom of the cell It was observed that the concentrate would flow on top of this tube thus misplacing and losing some of the material In order to solve this problem, a small funnel was fabricated and installed for the proper feed of this flow (as shown to the right of the picture) Any froth formed at the funnel would now flow into the interior of the flotation cell

A flotation cell of smaller volume was also fabricated in order to guarantee the proper process for very small flow rates

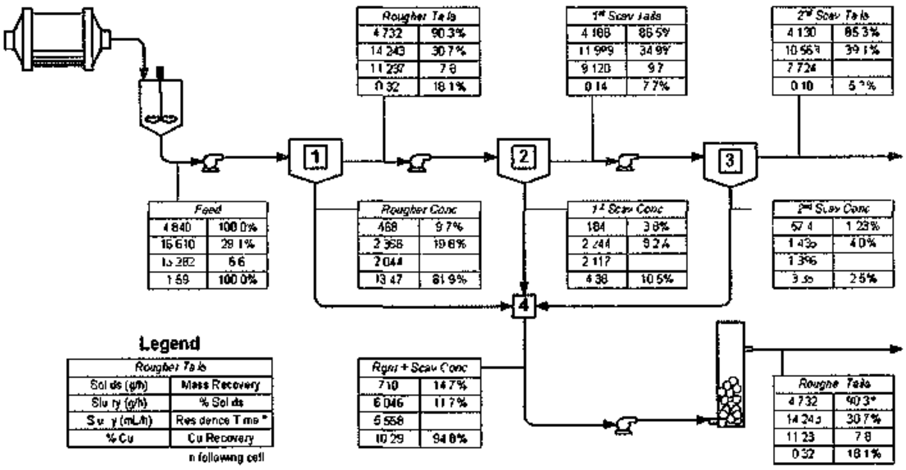

Figure 10 Simplified Flow Sheet Rougher and Scavenger Mass Balances

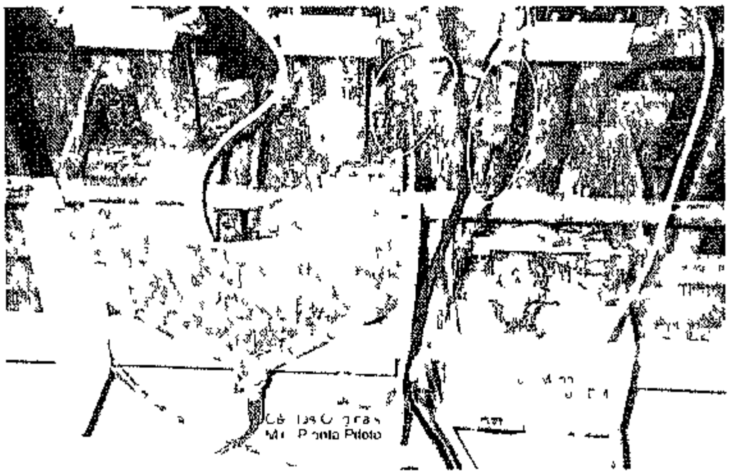

Figure 11 Cell Constructed at CMD and Cell Feeding SyslLm (white circles)

The addition of water into the launders (fine white hoses in the picture) was customized Recently, a froth crowder , circular in shape, was added to reduce cell surface area This device is used m the inside of the I mal cleaner cells

Comparative data for tests on Ore A are shown m Tables 2, 3 à. 4 and for Ore B in Talîles 5 & 6

Table 2 Comparative Data for Ore A

	Mini Pilot Plant			Locked Cycle Test			Open Circuit Test		
Flows	**Wt. %**	**%Cu**	**Cu Rec.**	**Wt.%**	**%Cu**	**CuRec.**	**Wt. %**	**%Cu**	**Cu Rec.**
Feed	100 0	141	1000	1000	142	100	100 0	132	1000
Rghr Cone	52	18 68	68 7						
Scav Cone	14 9	2 45	25 8						
Combined Cone	20 0	6 65	94 5	220	6 00	94 8	23 0	5 27	93 6
Scav Tails	80 0	0 10	57	78 0	0 09	49	77 0	011	64
1 ClnrFeed	30 3	6 83	146 6	410	5 00	142 8			
1 ClnrConc	77	20 09	110 2	17 0	10 40	1240	**5.0**	**23.30**	**79.5**
1 ClnrTail	22 5	2 28	36 4	240	1 11	18 4	190	0 92	13 2
Clnr Scav Cone	79	5 80	324	70	2 78	13 7	40	296	93
Clnr Scav Tail	147	0 39	41	170	042	49	15 0	0 35	39
2 Clnr Cone	**5.4**	**23.74**	**90.5**	**6.0**	**22.00**	**90.1**			
2nd ® ClnrTail	24	1178	19 7	110	4 38	34 3			
Final Tail	94 6	0 14	97	94 0	0 15	99	910	0 15	10 4

Table 3 Comparative Stage Testing for Ore A

	Copper Recovery - %			Enrichment Ratio		
Stage	**Open Circuit**	**Locked Cycle**	**MPP**	**Open Circuit**	**Locked Cycle**	**MPP**
Rougher + Scavenger	93 6	94 8	94 5	40	42	47
1st Cleaner	85 0	86 9	75 2	44	21	29
Cleaner Scavenger	70 2	74 1	88 9	32	25	25
2 Cleaner		72 7	82 1		21	12
Total Cleaner Circuit		95 1	95 8		37	36
Overall Circuit	79 5	901	90 5	17 7	15 5	16 8

Recirculating Load	18 1	10 2

Table 4 Comparative Data from the MPP and the Conventional Pilot Plant for Ore A

	%Cu	Recovery (%)
Mini Pilot Plant	36 0	86 0
Full Pilot Plant	37 0	87 0

Table 5 Comparative Data for Ore B

	Mini Pilot Plant			Locked Cycle Test			Open Circuit Test		
Flows	**Wt.%**	**%Cu**	**Cu Rec.**	**Wt.%**	**%Cu**	**Cu Rec.**	**Wt.%**	**%Cu**	**Cu Rec.**
Feed	100 0	120	100 0	100 0	127	100 0	100 0	131	1000
Combined Cone	69	17 20	96 2	71	17 23	96 3	74	17 23	97 2
Scav Tails	93 1	0 10	38	92 9	0 05	37	92 6	004	28
1 ClnrFeed	94	1560	119 4	95	13 94	104 2	74	17 23	97 2
1 ClnrConc	51	26 40	109 6	46	27 37	99 4	**4.0**	**30.59**	**92.9**
1 ClnrTail	43	2 80	98	49	125	48	34	165	43
Clnr Scav Cone	13	8 60	92	17	2 99	41	07	6 86	39
Clnr Scav Tail	30	0 20	05	31	0 29	07	27	0 20	04
2 Clnr Cone	**3.9**	**30.00**	**95.7**	**4.0**	**30.70**	**95.6**			
2nd ClnrTail	12	14 40	14 0	07	7 29	38			
Combined Tailings	96 1	0 05	43	96 0	0 06	44			

Table 6: Comparative Stage Testing for Ore B

	Copper Recovery - %			Enrichment Ratio		
Stage	**Open Circuit**	**Locked Cycle**	**MPP**	**Open Circuit**	**Locked Cycle**	**MPP**
Rougher + Scavenger	97.2	96.3	96.2	13.1	13.6	**14.0**
1 Cleaner	95.6	95.4	91.8	**1.8**	**2.0**	**1.7**
Cleaner Scavenger	4.6	85.0	94.5	4.2	**2.4**	**3.1**
2^{nil} Cleaner		96.2	87.2		**1.1**	**1.1**
Total Cleaner Circuit	95.6	99.3	99.4	**1.8**	**1.8**	**1.8**
Overall Circuit	92.9	95.6	95.7	23.3	24.2	24.5
Recirculating Load		2.4	2.5			

5. DISCUSSION OF RESULTS

Execution of the test work using different test methods permitted an evaluation of the type of data that can be obtained and reveals some of the limitations for each of the flotation processes tested.

Open Test

The open circuit test allows basic process parameters to be obtained. These parameters include development of a preliminary flowsheet, kinetics of flotation, reagent types and dosages and grinding requirements. It is an easy test to perform and requires very little ore (1 to 4 kg). The time and effort required to conduct a test is also small. This test provides good information with regard to the grade of the final products and the recovery in the rougher stage. For example, for Ore A, copper recovery in the open test rougher stage was 93.6% and in the Mini Pilot Plant it was 94.5%.

However, since it is a test without the intermediate recirculating flows, an open test does not allow an acceptable prediction of the total circuit recovery. This would be the case for an ore with difficult liberation characteristics and high recirculating loads such as Ore A. The cleaner stage recovery for this ore, in open test, was 79.5%, while in the Mini Pilot Plant test it was 90.5%. For an ore like Ore B, which is easily liberated and has good flotation characteristics with small circulating loads, total recoveries achieved in open tests are similar to produced in a continuous test. In this case, the cleaner recovery in the open test was 96.3% while in the MPP, it was 99.4%.

Beyond this, the quality of the final concentrate does not reflect the possible contamination by impurities carried by the recirculating streams.

Locked Cycle Test (LCT)

The LCT provides a good estimation of overall recovery for the rougher and cleaner circuits and does take into account the effects of the recirculating streams. For Ore A, the global cleaner recovery was 95.1%, while in the MPP a recovery of 95.8%. was achieved. For Ore B, the final circuit recovery obtained by the LCT was 95.6% and for the MPP it was 95.7%. The LCT can also offer a very good estimation of the circulation loads, depending upon the ore being tested. For Ore B, the values obtained by the LCT and MPP were 2.4% and 2.5%, respectively. On the other hand, for Ore A, a circulating load of 18% was obtained in the LCT compared to only 10% in the MPP.

The LCT is a more complex type of test, requiring a greater operational effort in relation to the open test and is similar to the effort required to run the MPP. The weight of sample required varies between 20 and 30 kg, which is also much greater than the weight required for the open test. A limitation of the LCT is its lack of operational flexibility, since the testing conditions of each cycle are pre-established and cannot be modified during the test procedure.

Since the LCT is operator dependent, the metallurgical difference between cycles, even though they are in equilibrium, may call results into question. Since the LCT must be carried out without interruption, the maximum number of cycles is normally between 10 and 15. When the ore is difficult and has a high recirculating load, this number of cycles may be insufficient to reach equilibrium.

Mini Pilot Plant and Conventional Pilot Plant

The principle merit of these two types of tests is their ability to test the process on a continuous basis. This is of major importance to the investor. The test in the MPP allows great operational flexibility and therefore permits optimization of operating conditions during its execution. With this method, it is possible to obtain trustworthy engineering data such as grades and recoveries of the various stages, as well as an evaluation of the influence of the recirculating load on the metallurgical performance

The MPP predicts, with sufficient confidence, the results obtained from a conventional Pilot Plant For Ore A the recoveries and final grades obtained in the MPP were 86% and 36% respectively, which were very close to those obtained in the conventional Pilot Plant, at 87% and 37% respectively The advantage of the MPP is even greater when one compares the ore requirements necessary to carry out both tests The MPP requires about 200 kg of ore, while the conventional pilot plant requires at least 10 tonnes of ore

With the MPP, the low sample requirement allows operation using drill core samples, which m turn allows a continuous circuit evaluation of the variability of the deposit without the need to develop underground adits This is major cost benefit, particularly for projects with uncertain economics

While the MPP is able to reproduce flotation results obtained in a conventional pilot plant, there are many other reasons for running the larger conventional pilot plants A conventional pilot plant allows generation of large quantities of products which can be given to potential clients for evaluation, for conducting grinding and filtration tests and so forth

6. CONCLUSIONS

The information obtained from the different flotation tests, performed at the different scales and flow conditions, are complementary As soon as the basic information is obtained in the bench scale tests, more complete and trustworthy information can be obtained as the complexity and dynamics of the tests increases In terms of evaluating flow recirculation and for obtaining a stable closed circuit operational regime, the LCT and MPP somewhat compete with each other, since the required effort to perform both types of test is very similar The MPP, with it's higher level of instrumentation, is easier to control and is less operator dependent MPP testing requires a greater amount of ore than the LCT, which may be a determining factor m defining the type of test to be carried out with certain ore types at the initial phase of the project However as the project develops and more detailed information is required for engineering studies, it will be necessary to carry out a series of tests m the MPP

The data obtained demonstrates that the metallurgical performance of the MPP is equivalent to that of a conventional Pilot Plant Since the MPP requires fewer personnel and significantly less ore, it can be concluded that the MPP is the equipment best suited to obtaining the data required for the engineering studies necessary to justify financial resources for the implementation of a new project

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