

FLOTATION MINI PILOT PLANT EXPERIENCE AT FALCONBRIDGE LIMITED

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Abstract

The use of Flotation Mini Pilot Plant Technology (MPP) has become increasingly more popular in recent years as an alternative to conventional piloting. The inherent advantages over conventional piloting include smaller sample size, reduced time to steady state and ability to perform variability analysis among others. Sampling and testing of the ore on an End-Member level is a key enabling technology to allow for use of a smaller sample size while stratifying the composite distribution. Falconbridge Technology Centre (FTC) has recently partnered with Canadian Process Technologies Inc. of Vancouver, B.C. in the specification, purchase and commissioning of a Mini Pilot Plant to support its process development and optimization efforts. The FTC Mini Pilot Plant is only the second such unit in use world wide and represents a new lower throughput limit in mini pilot technology. The FTC Mini Pilot Plant includes grinding, feed preparation, conventional cell flotation, pin mill regrinding, column flotation and reagent delivery, PLC control and PI data collection at nominal throughput rate of 10 kg/hr. The paper describes Falconbridge Technology Center experience in commissioning of the Mini Pilot Plant with a Cu/Ni/PGM sulphide ore followed by a validation of the technology while processing an existing ore using a current concentrator flowsheet. The End-Member sampling approach along with commissioning experience and modifications are discussed. Metallurgical results from the MPP and concentrator operating results are presented and compared. Further refinements and modifications for future project work are discussed.

INTRODUCTION

History

In the overall scope of evaluating either a new orebody for a new concentrator, or of optimizing an existing concentrator for improved treatment of existing orebodies, there are various scales at which the sampling and flotation testing of drill-core or mill feed are performed. All of these are designed to produce grade and recovery information that will be used to make processing or project decisions.

In the case of an existing concentrator treating sulphide ores, the flotation tailings produced by the concentrator contain the largest paymetal loss of all the unit processes that exist in the production of refined, saleable metal (Cramer, 2001). It is to be expected, therefore, that considerable effort has been made in the mineral processing discipline to

devise and implement various sampling and testing procedures that will inform operations and project staff of grinding and flotation opportunities.

The problem of obtaining reliable flotation test data from bench-scale testing used to exist. Before one could meaningfully conduct a laboratory scale flotation test, it was first necessary to prove that the sample of ore presented to the flotation test was representative. Further, it was necessary to demonstrate that the flotation test results were reproducible. Earlier work in South Africa addressed these problems. The work showed that a rigorous approach to the ore sampling and sample preparation protocols prior to the tests reduced the fundamental variance of the ore sample to 5%, with quantitative proofs of trueness. A series of replicated flotation tests with quantitative diagnostics for laboratory scale flotation testing of platinum-bearing ores improved the platinum accountability, and thus the reproducibility of results, across the flotation test (Lotter, 1995). High-Confidence Flotation Testing has been an accepted standard procedure at Falconbridge since 1997.

At the pilot plant level, tradition has honoured the conventional scale of pilot plant in order to demonstrate the grades and recoveries found at the bench scale. Such conventional pilot plants are continuous and treat 1-10 tonnes of crushed ore in a campaign. A short review of the published literature shows that:

1. There seems to have been the view that, because the size of the ore sample for the pilot plant is large (and often mined as a batch lot from a pilot shaft sunk in one location of the orebody), the bulk sample is 'representative', therefore the grades and recoveries of the pilot plant campaign must be true of that orebody.
2. There has been no reported attempt to perform replicate pilot plant trials, so as to find an average grade and recovery with associated confidence intervals, with the attendant benefits of reduced and normalized errors - a key effect of the Central Limit Theorem. (Box et al., 1978)
3. There has been no reported attempt to design, test and validate a quality control system that would verify the pilot plant results at a chosen confidence level.

In the case where limited amount of sample material such as drill core exists, Locked Cycle Testing has been the only alternative to simulating full scale flowsheets complete with circulating loads. Locked Cycle Testing is limited to simple flowsheets and has historically been difficult to establish and maintain steady state. To address these issues, Mini Pilot Testing has been developed. A comparison of various pilot schemes including Locked Cycle Testing is shown in Table 1.

Developments at Falconbridge

At Falconbridge, there has been a developing need for a smaller pilot plant which could simulate either existing operations flowsheets or new flowsheets, using smaller samples

of ore. The initiatives by the Exploration and Business Development groups of Falconbridge have identified several mineral resource targets that require flowsheeting and performance assessment at a suitable confidence level. Further, the development and use of Process Mineralogy at Falconbridge between 1997 and 2005 has resulted in a project approach that produces a Virtual Flowsheet ahead of flotation testing and thus significantly reduces the amount of sample material required for the characterization of the mineral resource or orebody (Lotter et al., 2002; Lotter et al., 2003). This has been a key development, since traditionally drill-core is in limited supply in an exploration program. Primary uses such as geological modelling, resource and cut-off grade estimation, and preservation of half-core for the purposes of due diligence consume much of the inventory of core.

End-Member approach

The identification and use of End-Members as a basis for resource estimation, sampling and testing was introduced as a procedure in the Second Generation of Process Mineralogy at Falconbridge (Whittaker et al., 2001). This clarified the understanding of the Raglan Concentrator in that the Massive Sulphides, Net-Textured Sulphides and Disseminated Sulphides all had individual, or distinct, metallurgical behaviours. This development led to a predictive model for future flowsheet improvements at Raglan (Fragomeni and Boyd, 2003; Fragomeni et al., 2005).

An End Member is a true, undiluted geological entity that has unique features such as:

1. Host rock type
2. Quantity and size range of sulphide mineralization
3. Degree of geological alteration, e.g. serpentinisation
4. Hardness
5. Grade and recovery performance

Geometallurgically, an ore end member is defined by a combination of textural, grain sizes and mineralogical features that can be grouped together based on the likelihood that they will perform similarly during grinding or flotation processes.

A further advantage of sampling and testing an orebody at the End Member level is to be found in the treatment of compound distributions. The drill-core and ore milled at the Raglan operation demonstrate fully spatial and residual compound lognormality, respectively (Lotter and Laplante, 2005; Lotter, 2005). According to published statistical theory, the optimum way of sampling and estimating the parameters of a compound distribution is by stratification of that distribution (Cochran, 1946). Where this is mathematically complex and outside the scope of this paper, the practice of identifying and sampling individual End Members physically stratifies the compound distribution, and reduces the overall variance of the paymetal distribution. This effect reduces the

minimum sample mass required for a fundamental variance of 5%, using standard published sampling models (Gy, 1979). Numerical exercises on this subject will be separately reported.

Table 1 – Comparison of typical Pilot options.

Flotation Testing Comparison	Bench Scale Open Circuit	Conventional PP – Lakefield, Strathcona, BMS	CPT Miniplant	Locked Cycle Test
Feed Rate Total	1-4 kg/test	200 kg/h	5-15 kg/h	15 kg/test (min 3 tests)
Origin	Drill Core	Large diameter drill holes: stope, ramp, tunnel	Drill Core	Drill Core
Primary Grind	Batch	Continuous	Batch	Batch
Regrind	Yes/Batch	Yes	Yes/Continuous	Yes/Batch
Flotation Cells	1-4 litre	Various 4-7-10 litre	12-24 each 1.7 litre	1-2-4 litre
Regrind/Cleaning Capability	N/A	Yes	Yes	Yes
Mobility	Yes	No	Yes	Yes
Information Obtained	Open Circuit Roughing and Cleaning only	Complete Circuit Design with Mass Balance and Circulating Loads	Full Circuit Design; Flowsheet Modification Design; Full Grade/recovery Curves	Circuit Design and Flowsheet Modification Impacts incl. Circulating Loads. Single Point Results
Issues	Obvious Preliminary Assessment Only; no Circulating Loads or Final Concentrates	Large sample and Cost Requirements. Issue with Sample Representativity. Continuous Primary Mill creates Instability.	Batch Grinding, must minimize feed tank retention time. Low sample requirement; easy to prove representativity. Ability to perform assessment on drill core and variability testing	Batch grinding and surface chemistry impacts exacerbate attainment of steady state. No potential recovery in event of instability or improper flotation conditions.

In the case of Mini Piloting, the use of the End Member approach is key to determine variability with ore type in the case of new projects. Drill core although limited in quantity is ideal for providing spatial representativity at an End Member level.

SPECIFIC OBJECTIVES

The specific objectives of this paper will be to review the commissioning of the Falconbridge Technology Center Mini Pilot Plant and communicate the implementation and results of a campaign performed in January 2005 to sample and test a known Raglan ore mixture in the standard Raglan flowsheet, in the Falconbridge Mini Pilot Plant at the Falconbridge Technology Center.

COMMISSIONING

Mini Pilot Plant equipment

The Falconbridge Technology Center Mini Pilot Plant (MPP) equipment was specified and ordered in October 2003 after an extensive review of the only other existing unit in the world at CVRD in Brazil (Fragomeni et al., 2003). The equipment was delivered by April 2004 and mechanical commissioning began. The MPP consists of 2 batch grinding mills, feed preparation and feed delivery tanks, 2 x 12 flotation cell continuous flotation machines, 2 flotation columns and reagent delivery system and a PLC interface.

During the commissioning, Falconbridge Limited Fraser Cu ore, a high grade Cu/Ni/PGM ore presently being mined was processing in the Mini Pilot Plant using a Virtual Flowsheet developed for the Ni Rim South Footwall, an End-Member which is mineralogically similar to Fraser Cu. The commissioning campaign commenced in June 2004 and operated over a 4 day period.

Each piece of equipment is described in subsequent sections along with commissioning issues and refinements.

Rod mills

Two identical 12"x18" rod mills were delivered as part of the mini pilot plant (MPP). These mills have been designed to batch-mill ore charges of up to 10 kg for pilot plant feed, but their design also allows their use for laboratory batch flotation tests. During the campaign, only one mill was operated at grinding media volumetric loading of 25%.

A photo of one of the rod mills is shown in Figure 1.



Figure 1 – Mini pilot plant grinding mill.

In order to reduce the manpower requirements for grinding a lifting mechanism was developed that is activated by a hydraulic actuator (the mill is shown in the loading position in Figure 1). Once the grinding process is completed, the entire mill content is discharged into a specially designed cart that facilitates easy grinding media washing and minimizes materials handling. Further refinements include a basket arrangement installed on the mill discharge to eliminate the need to remove all the grinding media when discharging the ground slurry.

Two smaller mills were selected to allow for more frequent batch grinding of smaller batches to eliminate large retention times of sulphide slurry prior to flotation. Investigation prior to purchasing the MPP identified this retention time should be maintained at between 30 minutes and 1 hour in order to maintain surface chemistry prior to flotation (Hoffman et al., 2003). This was considered in the design of the mill and tanks.

Holding and feed tanks

Slurry that has been ground in the rod mills is transferred to the holding tank for slurry SG and pH adjustments. The holding tank is equipped with a pH probe to facilitate easy pH adjustment. Once the feed density is adjusted the slurry is transferred into the feed tank in a batch.

The primary objective of the feed tank is to provide a continuous and consistent slurry flow to the flotation units. Key components on the skid are the feed tank as well as an agitator and circulating pump that ensure homogenous slurry inside the tank. The slurry is transferred to the flotation units via a double-headed variable speed hose pump. The advantage of employing a double-headed pump is that it facilitates feed sampling without disrupting the flow to the flotation units. The second slurry hose typically only recirculates back into the feed tank. A timed sample is automatically directed to a sample pail from the second slurry hose discharge. Figure 2 shows a photo of the feed tank.



Figure 2 – Mini pilot plant feed tank.

Continuous flotation machines

The key components of the new flotation mini pilot plant are the two continuous flotation machines (CFM). Each of these units comprises twelve 1.5-Litre flotation cells including associated auxiliary equipment such as Denver type agitators with variable speed control, air addition with automated air flow control, variable speed froth paddles, launder water lines, transfer pumps and launders. A back-view of a flotation unit with three triple-header transfer pumps is shown in Figure 3. With this design, numerous flowsheet combinations can be readily tested by simply re-arranging the launder and transfer pump configuration.

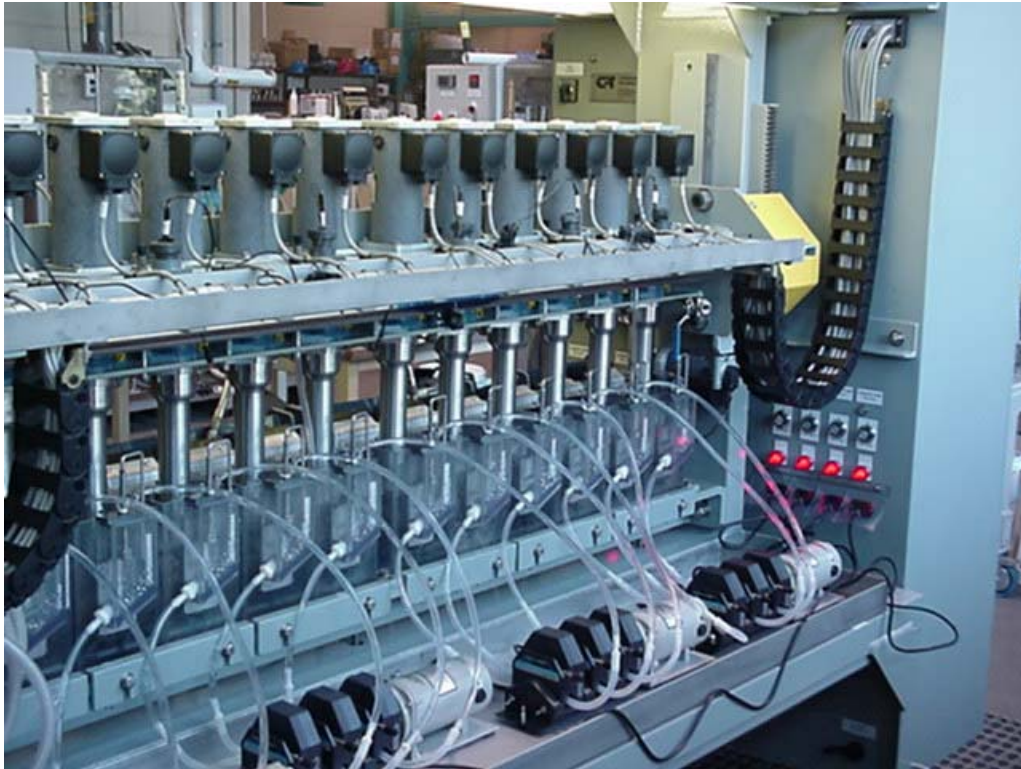


Figure 3 – Continuous flotation machine (CFM).

A major re-design of the flotation cell drive system was necessary prior to commissioning of the MPP. The direct drive motor-shaft-impeller coupling was not adequately supported in the original design which resulted in vibration during high speed rotation. The diffusers were shortened and a bearing housing similar to that used in the lab scale Denver cell were fabricated for each agitator. CPT was very cooperative in supplying the technical and financial resources to implement this change.

The Virtual Flowsheet tested took advantage of the coarse chalcopyrite grain size and included a coarse particle flotation stage. During the CFM commissioning period, sanding out of the flash flotation cells was observed due to the coarse feed size of $p_{80}=300$ microns. In order to eliminate this problem, sand ports were installed at the bottom of the two flash flotation cells to facilitate coarse tailings removal with the aid of a hose pump. This proposed solution was tested successfully prior to the commissioning campaign with only 2 occurrences of plugged sand relief lines.

The lime distribution systems on the CFM's were successfully commissioned thus eliminating the need to manually add lime to the feed tank. The lime was made up at strength of 0.2% and distributed and added using a lime loop and pinch valve combination while the pH was automatically maintained using a standard PID controller. A total of 6 such pH control loop/Eh measurement combinations are available on each CFM.

PIN regrind mills

The flotation mini pilot plant includes two pin mills for regrind purposes. One such mill is shown in Figure 4.



Figure 4 – PIN regrind mill.

The regrind pin mills can be used in a Staged Grind approach or can be used to continuously regrind rougher concentrates or cleaner tailings depending on the flowsheet considered.

The grinding action is obtained with the aid of small pins that are mounted horizontally on a vertical shaft. The shaft and pins rotate in a cylinder filled with grinding media (6mm diameter stainless steel balls during this campaign), which generates the desired grinding action. The feed enters the mill through the bottom side port and moves upwards through the grinding chamber to be discharged at the top side port. Grinding conditions can be varied through the selection of the height of the discharge port and the mill speed.

Modifications of the feed screen designed to retain media in the mill were required prior to the commissioning run. Also, significant wear was experienced on the pin mill shaft and pins. A surface hardening coating was applied to the shaft and has proven successful in maintaining integrity during subsequent pilot runs.

Flotation columns

In order to facilitate cleaning as practiced in commercial plants, the mini pilot plant includes one 50 mm and one 75 mm diameter flotation column. A picture of the 50 mm flotation column in operation is shown in Figure 5. The pilot column includes all pertinent features of commercial units such as wash water system and air spargers. In order to achieve level control in the column, both units are also equipped with pressure gauges (DP cells) that work in conjunction with the stand-alone PID controller and provide automated level control.

The flotation column was used at the end of the commissioning run for Cu/Ni separation. Subsequent runs have used for the columns for 2-stage cleaning as will be discussed later and in Cu/Ni separation service. Modifications after the commissioning runs included improved distribution of wash water, PI monitoring of column operating parameters and improved feeding and sampling practices.

Reagent cart

A total of 16 small positive displacement pumps on the reagent cart provide continuous reagent flow to the various flotation cells. Figure 6 shows a side-view of the reagent cart with 8 pump heads and controllers. This specific type of pump was selected, because it is capable of delivering very low flowrates at high accuracies, which is paramount to avoid unnecessary dilution of the reagents and therefore the slurry. The typical operating range of the pumps during the commissioning campaign was between 5 ml/min and 15 ml/min.



Figure 5 – 50 mm diameter flotation column.

In order to facilitate large dosage differences for the various reagents on a gram per tonne basis, the dilution ratio was selected so that the pump would not operate below 5% while minimizing reagent dilution. Therefore, dilution as low as 0.025% is not uncommon. With these dilution rates and flowrates typical reagent re-filling is required between every 4-6 hours. This is preferred to reduce the impact of solution degradation at these low concentrations.



Figure 6 – Reagent delivery cart.

PLC/PI system

The individual components of the MPP are tied into a Modicon PLC system programmed in the Concept programming language. The PLC operator interface is accomplished by a Wonderware MMI and is used, for example, to change setpoints for airflow on any conventional cell or trend the feed flowrate. A typical operator interface trend screen is shown in Figure 7.

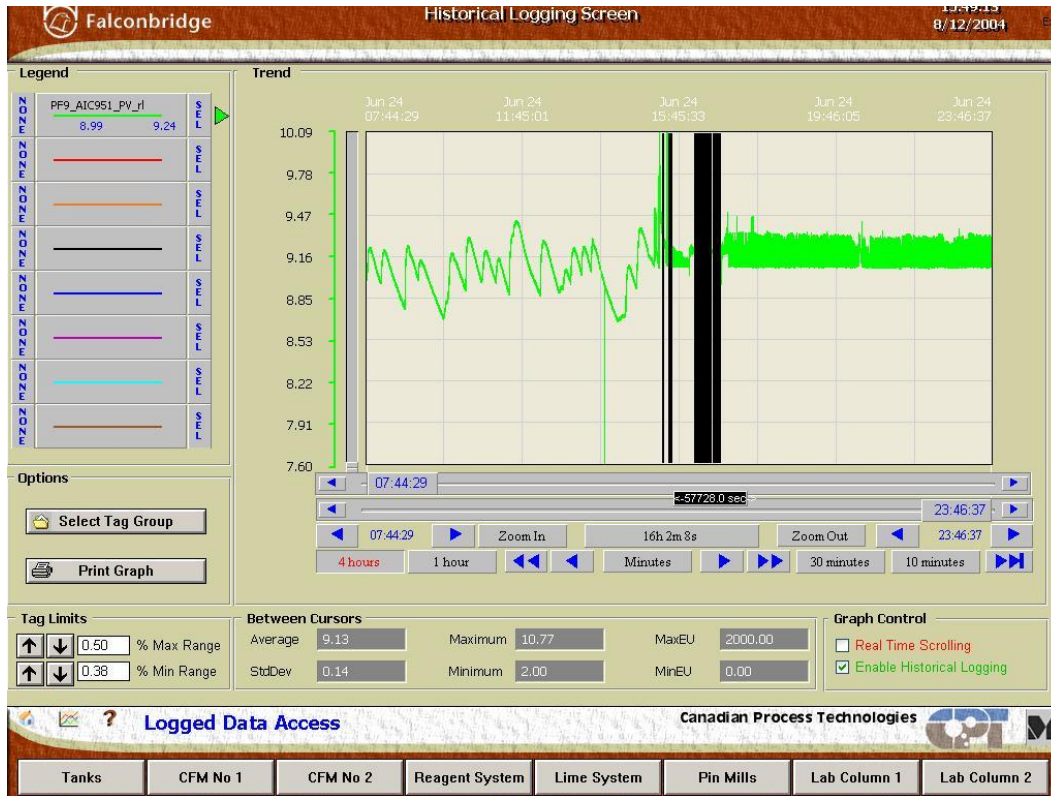


Figure 7 – Typical MMI screen.

Flowsheet

The flowsheet tested during the commissioning campaign was the latest version of the proposed Nickel Rim Virtual Flowsheet consisting of staged grinding and flotation. The flowsheet includes flash flotation roughing, scavenging and cleaner flotation as shown in Figure 8. In addition to the expected mass flows, Figure 8 also depicts the reagent addition points as well as the sample ID number (1-18). Furthermore, Ni-Cu separation of the bulk concentrate was performed in an effort to commission the pilot plant flotation columns as shown in Figure 9.

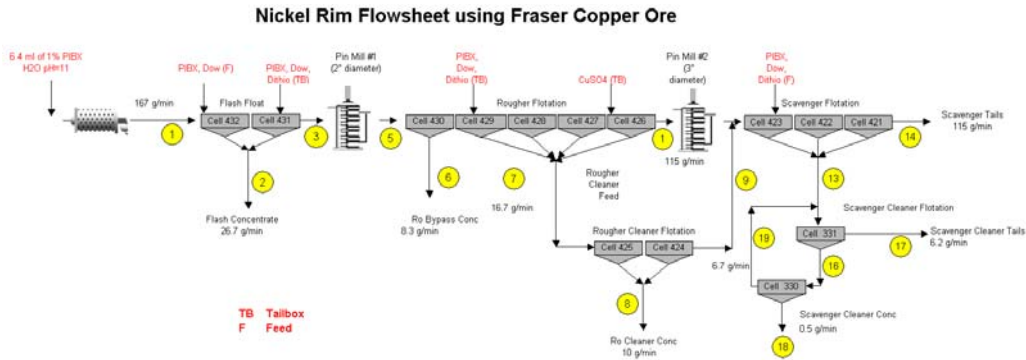


Figure 8 – Fraser Cu commissioning flowsheet.

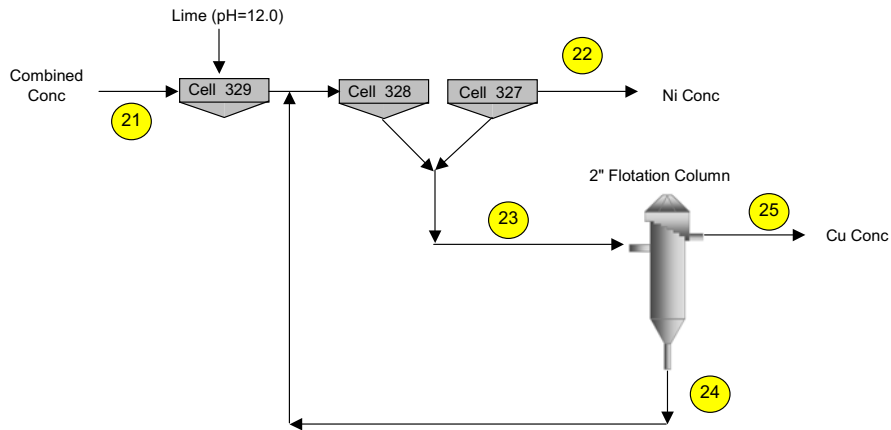


Figure 9 – Fraser Cu commissioning Cu/Ni separation.

Sampling model

The are 3 levels of sampling in the MPP sampling model are Steady State Verification, Open Sampling and Closed Sampling. Steady state verification and is an accounting of the sum of all product mass flows and comparison to the MPP feed rate.

The difference between open circuit samples and closed circuit samples is important because they have different consequences for the stability of the pilot plant. Open circuit samples are the battery limits of the flotation circuit namely final concentrates and tailings. Multiple open sampling is performed and produces an external reference distribution of Ni grade and mass for comparison to the more intrusive closed sampling. The collection of the open circuit samples does not include any internal streams, thus

does not affect the stability of the pilot plant. Closed circuit samples on the other hand include all internal streams and can be used to Bilmat balancing and complete internal mass balance for recovery projection and plant design.

Commissioning summary

In order to validate the closed circuit sampling, the assays generated from the closed sampling were compared to the upper and lower confidence limits of the open assays. Using the Statistical Benchmark Survey criteria, the feed assay of the closed sampling should fall with the acceptance limits of the open sampling (Opening Sampling External Reference Distribution) (Lotter, 2006). As shown in Table 2, the Closed Sampling Ni and Cu assay fall within the external reference distribution of the Open Sampling. The feed assay of the closed sampling is within 3.3% of the external reference distribution of the feed. The survey result therefore meets the Statistical Benchmark Quality Criteria.

The Metallurgical results were consistent with expected lab scale results and are shown in Table 3.

The commissioning campaign was completed over a 4 day period in June 2004. Plant operating time was 100% with no downtime attributed to equipment failure. A total of 4 plugged lines caused 1.25 total hours of instability. All the plugging occurred in the flash cell and 1st regrind pin mill. A failure of the CFM #2 froth paddle drive required some mid-campaign maintenance causing 2 hours of instability. The key findings and modifications from the commissioning campaign were:

- Feed flow maintenance and control – A magnetic flowmeter capable of measuring and subsequently controlling the feed flow should be installed.
- The transfer of slurry from the batch mill to the holding tank was automated to minimize manual handling and improve productivity.
- Column experience is required
- Flotation of coarse feed sizes ($p_{80}=300 \mu\text{m}$) is feasible however the degree of mixing the holding and feed tank is high requiring more horsepower and improved mixer design. The existing design is temporary and requires a permanent solution.

Table 2 – Open and closed sampling.

2a Nickel				
No.	Feed	Call Factor	Sum of Concs	Sum of Tails
1	0.78	1.01	2.60	0.07
2	0.80	1.04	2.72	0.07
3	0.76	0.99	2.78	0.07
4	0.78	1.01	2.62	0.05
5	0.81	1.05	2.55	0.06
6	0.79	1.03	2.57	0.07
Mean	0.79	1.02	2.64	0.07
Std Dev	0.018		0.091	0.008
RSD%	2.23		3.43	12.87
2 Std Dev	0.035		0.181	0.017
UCL	0.82		2.46	0.05
LCL	0.75		2.82	0.08
Closed	0.78		2.48	0.07
Bilmat	0.75		2.58	0.07

2b Copper				
No.	Feed	Call Factor	Sum of Concs	Sum of Tails
1	5.56	0.98	20.35	0.04
2	5.65	1.00	20.36	0.05
3	5.54	0.98	20.50	0.05
4	5.78	1.02	20.74	0.04
5	5.80	1.02	20.72	0.05
6	5.70	1.01	20.75	0.07
Mean	5.67	1.00	20.57	0.05
Std Dev	0.109		0.190	0.011
RSD%	1.92		0.93	21.91
2 Std Dev	0.218		0.381	0.022
UCL	5.45		20.19	0.03
LCL	5.89		20.95	0.07
Closed	5.66		20.88	0.052
Bilmat	5.65		20.85	0.052

Table 3 – Commissioning Fraser Cu run metallurgical results.

Ni		Cu	
Conc Grade %	Recovery %	Conc Grade %	Recovery %
2.48	93.25	20.88	99.22

RAGLAN VALIDATION CAMPAIGN

Objectives

Following the commissioning run and the confirmation of mechanical stability and metallurgical consistency, a validation campaign was scheduled.

The campaign had the following primary objectives:

- Validate that metallurgical results generated in the MPP are comparable to a full-scale operation (Raglan) with the plant flowsheet;
- Evaluate the circuit performance at an increased feed rate (from 10 kg/hr to 14 kg/hr). This increase in the pilot plant is equivalent to a Raglan concentrator feed rate increase from 112 t/hr to 157 t/hr.
- Gain experience into the operation of the two flotation columns;
- Confirm the sampling model for a typical nickel ore with multiple cleaning stages.

Sample preparation

The 750 kg bulk ore sample prepared for the MPP campaign was prepared from weighed individual bulk samples of the Raglan End-Members. Footwall (gabbro) waste was also sampled and added. Table 4 summarizes the weights of each component.

Table 4 – Makeup of campaign ore sample.

End Member	% wt in Overall Sample
Massive Sulphides	6.1
Net-Textured Sulphides	65.9
Disseminated Sulphides	16.0
Gabbro Footwall Waste	12.0

Each of the above components were separately crushed and blended to a topsize of 1.7 mm. The blending was performed using a large spinning riffler and using the two methods called odds-and-evens blending and subsampling (Lotter and Stickling, 2000). This procedure reduces the group and segregation error and provides for subsamples, or test charges, that demonstrate less than 5% relative standard deviation in the sample mean grade of paymetal (Lotter, 1995). From each separately crushed and blended sample of End Members, weighed subsamples were extracted and added to the composite. The mixture was again blended and subsampled using the spinning riffler. In this way, batch-to-batch variation as rougher float feed to the mini pilot plant is reduced and steady state in the flotation circuit is attained more rapidly. The external reference distribution of this overall composite sample was extracted using the spinning riffler. A total of ten replicate subsamples was taken and presented for chemical analysis. The results are shown in Table 5.

Table 5 – External reference distribution of overall Raglan ore sample.

Sample Number	Ni %	Cu%	S%	MgO%	Fe%
1	2.86	0.81	9.90	22.8	19.0
2	2.82	0.81	9.96	23.0	19.2
3	2.86	0.81	9.87	23.0	19.2
4	2.86	0.81	10.1	23.0	19.2
5	2.85	0.80	10.0	23.0	19.2
6	2.83	0.81	10.1	23.1	19.2
7	2.88	0.81	10.2	23.2	19.2
8	2.84	0.80	10.1	23.2	19.2
9	2.81	0.81	10.0	23.2	19.1
10	2.85	0.81	9.95	23.2	19.2
Mean	2.85	0.81	10.02	23.07	19.17
Std. Dev. %	0.021	0.004	0.104	0.134	0.067
(1)	0.74	0.52	1.04	0.58	0.35
RSD % (2)					

Notes:

Std. Dev.: Standard Deviation

RSD: Relative Standard Deviation

Inspection of Table 5 shows that, in all cases, the relative standard deviations of the sample means are less than 5%. This sets the foundation for minimal variance in batch-to-batch feed characteristics during the MPP campaign.

CAMPAIGN OPERATION

Flowsheet

The standard Raglan flowsheet used is shown in Figure 10. Typical mass flows and grades for the production operation were obtained from a previous Statistical Benchmark Survey of the production concentrator (Fragomeni et al., 2004), historical plant data and a prediction model developed by Raglan to benchmark performance (Ciriello et al., 2004) and are shown as targets.

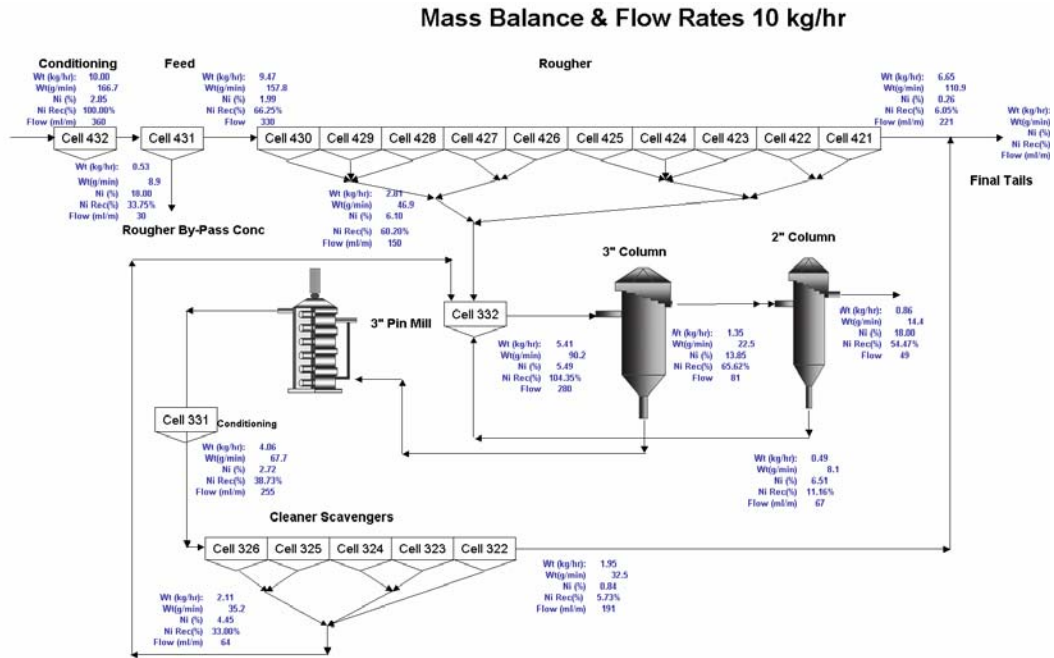


Figure 10 – Raglan flotation flowsheet.

Grinding was carried out in batch ball mills. In order to ensure that feed preparation mixing and conditioning had minimal impact on pulp chemistry (oxidation), 5 and 7 kg batches were ground every 30 minutes prior to introduction into the MPP feed tank. This 30-minute guideline was based on testwork performed in 2003 (Hoffmann, 2003). This ensured that the slurry was exposed to mixing a maximum of 30 minutes prior to conditioning with reagents. A measurement of the feed slurry during the campaign yielded a redox potential of -50 mV thus indicating that slurry and mineral surface oxidation was unlikely.

MPP flotation feed size distribution produced from the batch ball mill was measured and compared to plant size distribution. The p_{80} size of $68 \mu\text{m}$ was determined from grind versus batch time curves and therefore matched the target p_{80} . The plant contains slightly more fines than the MPP feed with about 5% more -9 micron, 1-2% more $+150$ micron and $+106$ micron material. The results are shown in Figure 11. This type of deviation is typical of batch versus plant grinding and is also observed in conventional pilot plants, which use either small cyclones or screens in closed circuit continuous mills. Optimization of ball charge (adding more small balls) could correct these differences observed however small deviations are likely to remain.

Synthetic process water with average plant salt concentrations was used for grinding and pulp density make-up. Tailings and concentrate water was not recycled back to grinding.

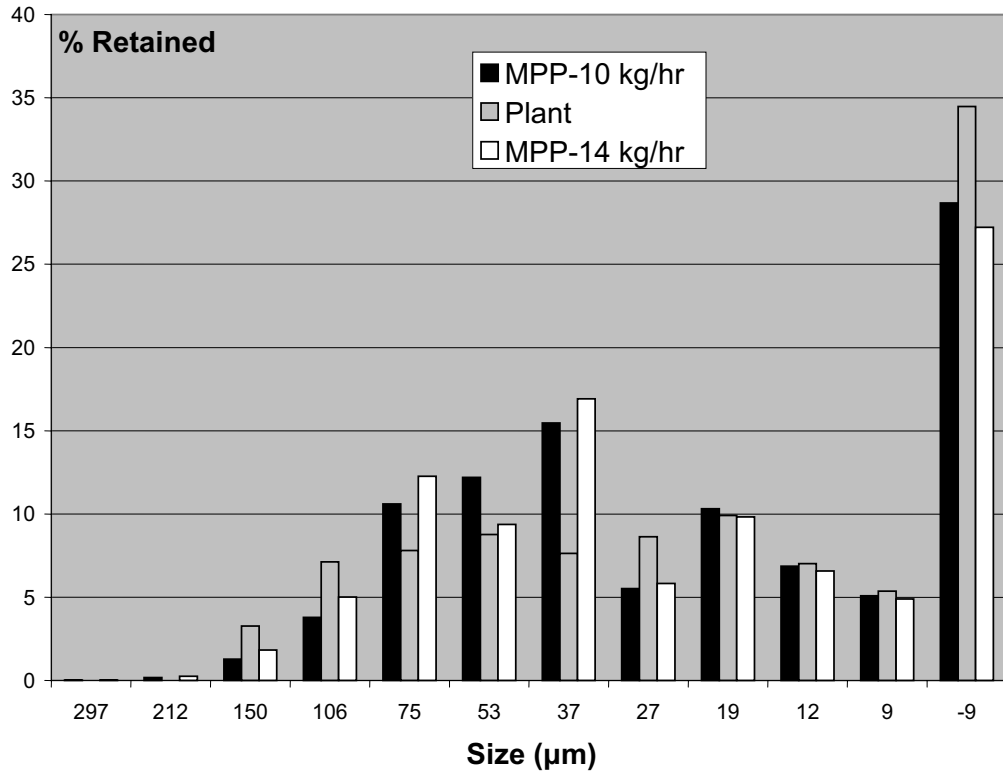


Figure 11 – Raglan mini pilot plant batch grinding size distribution comparison.

Two feed rates were tested in the MPP run, 10 kg/hr equivalent to 112 t/hr at Raglan and 14 kg/hr equivalent to ~157 t/hr at Raglan. The number of required rougher and cleaner scavenger cells was determined based on plant residence time with a 0.8 volume factor. No additional scale up, or in this case, scale down parameter was used from the plant conventional cells to the MPP conventional cells.

The MPP column retention time was considerably lower than in the plant. However, the more critical surface areas were proportional to the plant between the 1st and 2nd cleaners and column area loading did not exceed the maximum design parameter.

PIN mill regrinding was carried out on the 1st cleaner tails as in the plant with excellent agreement between the MPP and plant size distributions as shown in Figure 12. The target regrind size was a $p_{80}=25 \mu\text{m}$.

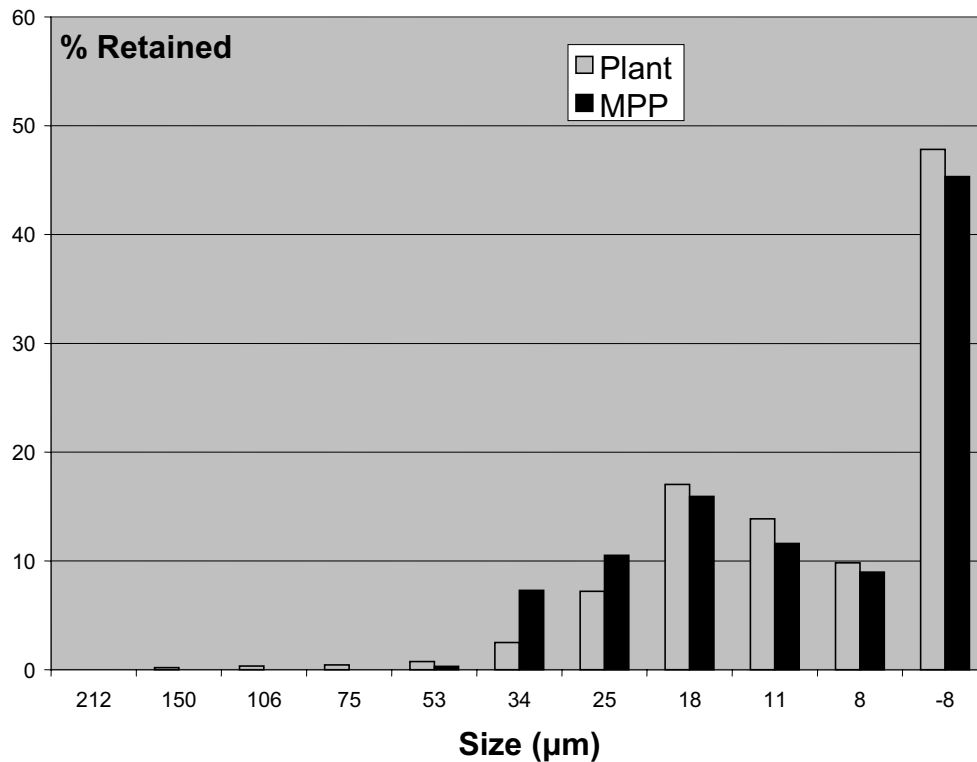


Figure 12 – Raglan mini pilot plant cleaner scavenger feed size distribution.

RESULTS AND DISCUSSION

The Ni and Cu grade and recovery performance of the MPP closed sampling compared well to Raglan plant as shown in Table 6. Overall Ni grade and recovery in the MPP are almost identical to historical (avg. 2000 to 2005) plant performance. The MPP Ni metallurgy exceeded modeled (Raglan Performance Model: Ciriello, 2005) grade and recovery for an ore with similar Fe/Ni ratio. The MPP Ni metallurgy was consistent with the targets. When considering the confidence limits, MPP metallurgy agreed well with all metrics.

Copper recovery is slightly below target. A comparison of the copper losses in the tails between MPP and Plant reveals that the elevated copper losses occurred in the MPP rougher tails and not in the cleaner scavenger tails. However, the plant performance is highly variable with a 95% Confidence interval on recovery of +/-6.06%. Furthermore, Cu rougher recovery in a lab scale flotation test was 79.7% with this ore. Therefore, the MPP Cu recovery is within the variability of the plant and compares well.

Table 6 – Grade and recovery in final concentrate (10 kg/hr).

Metal	Description	Grade %	Recovery %
Ni	MPP Actual	18.15 +/- 0.15	87.91 +/- 1.82
	Plant Actual (Historical)	18.31 +/- 1.73	87.92 +/- 3.39
	Plant Model	17.6	86.4
	MPP Target	18	88.2
Cu	MPP Actual	4.71 +/- 0.05	79.88 +/- 1.56
	Plant Actual (Historical)	5.13 +/- 0.79	84.30 +/- 6.06
	Plant Model	N/A	82.2
	MPP Target	5.0	82.0

As shown in Table 7, final concentrate MgO assays from the MPP campaign agreed well with the November 2003 survey and plant performance.

Table 7 – MgO assays of final concentrate.

Description	MgO Grade
MPP Actual	4.4
Plant Actual (Historical)	5.2
November 2003 Survey	4.6

The MPP rougher by-pass, rougher and overall performance for the 10 kg/hr and 14 kg/hr conditions is shown in Figure 13. For comparison purposes February 2000 survey data along with November 2003 plant survey data is shown in the same graph. The bypass rougher in the MPP and the plant produced similar metallurgical performance achieving +18% Ni grade at between 30-40% Ni recovery. The February 2003 bypass grade performance is superior to the November 2003 surveys and the MPP due to higher head grades in February 2003. (3.6% Ni versus ~2.8% Ni). Good agreement was achieved between the November 2003 surveys and both 10 and 14 kg/hr runs in the rougher. Once again the February 2003 survey produced a higher overall rougher grade due to higher feed grades. Finally, overall concentrate grade and recovery performance were along the same grade/recovery curve for all the MPP campaigns and survey data.

Although an initial concern, oxidation did not affect the Ni flotation kinetics in the rougher circuit. The pilot plant kinetics curve for the 10 kg/hr base case is shown in Figure 14 together with the November 2003 survey rougher performance and lab scale batch flotation results. The graph clearly illustrates that the pilot plant kinetics matched the one of the commercial plant. Also a scale up ~2 from lab data is shown to be reasonable for both MPP and plant data.

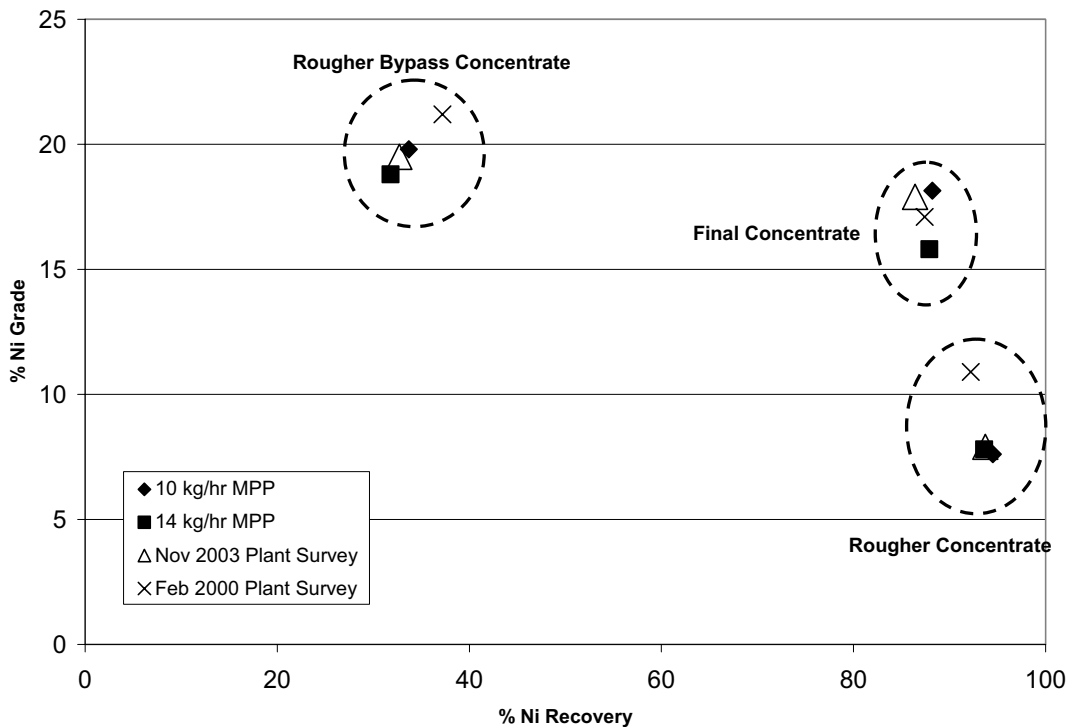


Figure 13 – Raglan Mini Pilot Plant comparison to Plant metallurgy.

Selectivity between Po and Pn was also similar in the MPP versus the full scale plant using results from the Statistical Benchmark Surveys in November 2003, February 2000 and June 1998 as shown in Figure 15. Note that the mineral calculations are based on estimates from chemical analysis. The only way that minerals can be quantitatively measured is using quantitative mineralogy.

The Raglan flowsheet utilized both MPP flotation columns. Valuable operating experience was acquired during this first continuous run using columns. After initial adjustments, the columns were able to produce a metallurgy that was comparable with the Raglan columns. A number of minor modifications such as improved level control and wash water delivery system have been identified and will be implemented prior to the next campaign.

A comparison of the rougher and cleaner nickel unit recoveries at 10 kg/hr and 14 kg/hr was performed. At 14 kg/hr the rougher nickel recovery decreased by 0.85% at a slightly higher rougher concentrate grade (+0.17%). This reduction in rougher recovery is in the same range as that predicted at higher tonnage rates through the Raglan rougher (Fragomeni et al., 2005).

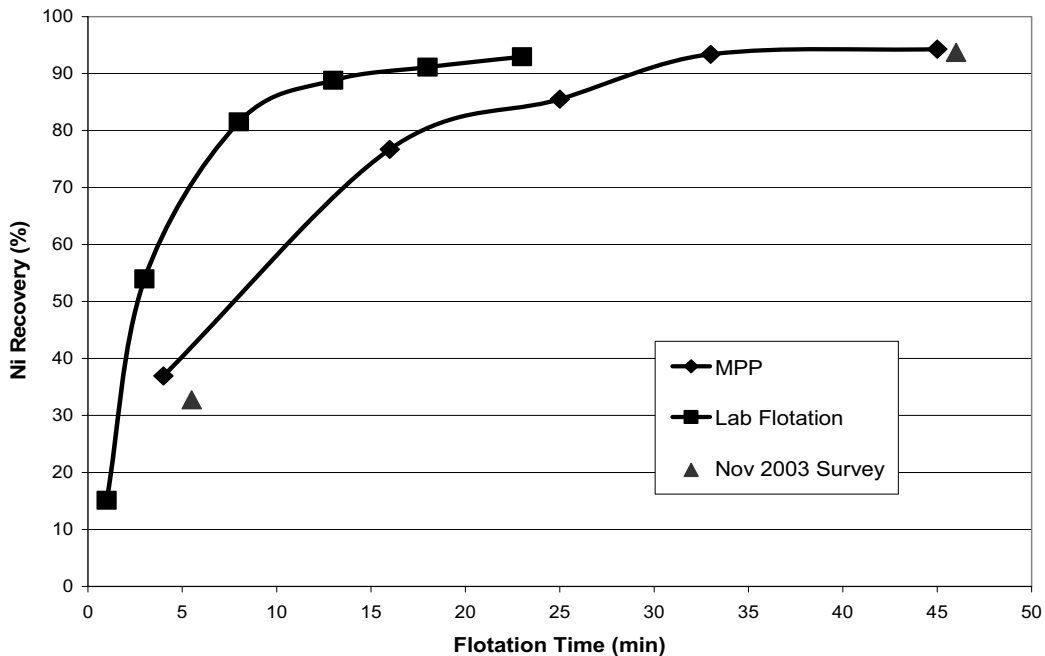


Figure 14 – Nickel flotation kinetics (10 kg/hr).

In the cleaning circuit, selectivity was much poorer at the higher feed rate. Although the unit recovery improved by 1.1%, the nickel grade in the 2nd cleaner concentrate decreased by 2.8%. The 2nd Cleaner appears to be clearly off its normal grade/recovery curve. This could be due to the higher area loading experienced at 14 kg/hr (0.67 t/hr/m²).

The initial sampling model proved successful during the Fraser Cu commissioning campaign. However, due to the more complex flowsheet at Raglan and the larger circulating loads, more time is required to reach steady state. In the case of the 10 kg/hr run, open samples were taken 9 hours after making significant cleaner circuit adjustments. In this case open samples were taken too soon while the circuit was still unstable. It has been concluded that the open circuit samples were taken while the circuit was still stabilizing in the case of 10 kg/hr run.

Due to the low flow rates in the pilot plant, slurry dilution resulting from wash water and reagents addition is a concern. Hence, an effort is made to minimize wash water addition and to maximize reagent strength within the physical limitations of the reagent pumps. In order to assess the suitability of this operating strategy, the solids concentrations of the various pilot plant streams are compared to the plant streams. The results of this comparison are summarized in Table 8 and show that critical streams such as the rougher concentrate or the cleaner scavenger feed have similar and in some cases higher solids

concentrations in the MPP and the plant. Hence, this operating strategy is considered successful and will be used in future campaigns. Furthermore, the good agreement between pilot plant and plant data also supports the use of the pilot plant mass and volume balances for circuit design and sizing.

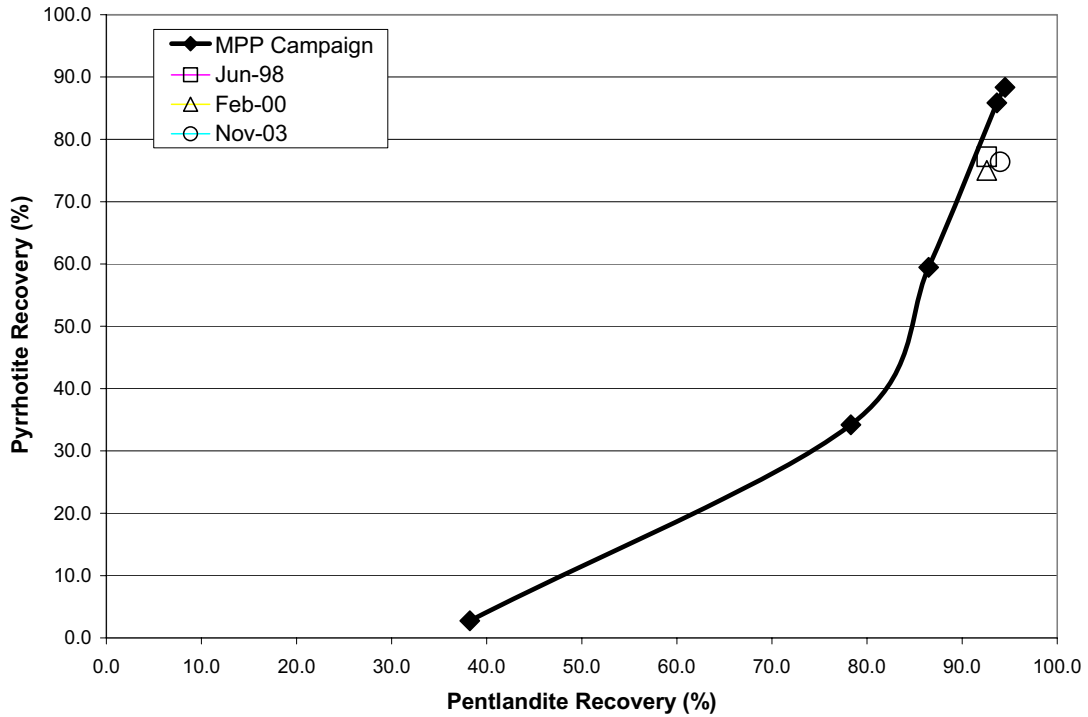


Figure 15 – Po/Pn selectivity (10 kg/hr).

Table 8 – Plant and MPP solids concentrations.

	MPP 10 kg/hr	MPP 14kg/hr	Raglan Plant
Feed, %	35	35	37
Ro By-pass conc, %	44	42	22
Rougher concentrate, %	29	30	24
Rougher tails, %	28	31	34
1 st cleaner concentrate, %	29	37	20
2 nd cleaner concentrate, %	16	22	30
Cleaner scav feed, %	22	16	19
Cleaner scav tails, %	15	11	11
Cleaner scav conc, %	38	23	23

CONCLUSIONS

Overall the MPP produced results that are consistent with Raglan plant performance. Grade and recovery targets were met and fall within the 95% confidence limits of plant results achieved during the last 4 years. Overall plant grade and recovery performance can be reproduced in the MPP. Selectivity between Pn and Po are similar in the MPP versus the plant. Percent solids in the MPP are comparable to the plant and therefore, volumetric flows could be used for plant design. The problem of low cleaner circuit densities normally experienced in pilot plants has been overcome.

Mechanically the pilot plant operated without any major problems with the exception of four occurrences of plugged lines. It was concluded that the reason for the plugged feed line was the result of quick connections used to facilitate rapid hose replacements. Once these quick connects were removed from the feed line no further blockages were observed.

The initial sampling model proved successful during the Fraser Cu commissioning campaign. However, due to the more complex flowsheet at Raglan and the larger circulating loads, more time to reach steady state was required. Therefore, the open samples were taken prior to establishing steady state. Open samples were taken 9 hours after making cleaner circuit adjustments. This experience demonstrated that sampling was performed too soon and that cleaning circuit stability is only reached after a longer period of time. It is envisioned that at least 12 hours is required after a major process change to re-establish steady state.

The experience gained during this campaign identified a need for 2 additional pieces of process control. A hand-held XRF for quick assay turn around is being considered. This will allow for fast turn around on control samples while minimizing sample preparation requirements. Furthermore, the technical feasibility of performing continuous and automated mass flow measurements on the feed and tails streams is being evaluated to aid the metallurgist to better evaluate the stability of the circuit. Other improvements including, trending of available pulp output speeds on VSD drives will be used for assessment of steady state.

FURTHER WORK

As a result of these pilot plant campaigns a number of improvement activities have been identified and implemented:

- Automate feed flow measurement and control to ensure that the slurry and solids flow rate to the flotation circuit remains constant at all times;
- Optimize control strategy for columns tailings pump.

- The wash water system of the flotation columns proved difficult to control. Furthermore, pressure drops in the main water header resulting in fluctuating flow rates to the columns. In order to eliminate these problems, a regulator and high precision valves has been installed in the wash water supply line;
- Sampling of the column concentrates was difficult and froth holdup in the discharge line was a concern. Positive displacement pumps were installed at the discharge line of the two flotation columns to ensure that all concentrate is removed from the column as soon as it reports to the column overflow;
- The analysis of the Raglan MPP data showed that open circuit sampling commenced although the circuit was still ramping up to steady state. The acquisition of a hand-held analytical device will help to provide very quick turnaround time for analysis of samples, (~2 hrs) thus allowing frequent sampling and an assessment of the circuit stability at a higher confidence level;
- Further refinements could include the development of an on-stream analyzer similar in design to the Courier 300;
- A new system to transfer slurry from the grinding area to the holding tank has been developed.
- Perform RTD (Residence Time Distribution) testing on the MPP to confirm the short-circuiting and scale up factors to be used between laboratory, pilot and plant scale.
- Fabricate continuous thickeners to allow for water recycle.
- Monitor CVRD's experience in the plant performance of the newly commissioned Sessego copper plant. The flowsheet at Sessego was designed with MPP data.

ACKNOWLEDGEMENTS

The authors would like to thank the management of Falconbridge Ltd. for permission to publish this paper. The staff and technicians of the Falconbridge Technology Center (FTC) have made valuable contributions to this program. This includes the Process Control Group, and in particular Erik Bartsch. The contribution of Oliver Peters, formally of FTC, is acknowledged. The cooperation of Canadian Process Technologies in manufacture and delivery of equipment in a condensed timeframe along with cooperation in redesign, fabrication and commissioning is greatly appreciated.

REFERENCES

- Box, G.E.P., Hunter, W.G. and Hunter, J.S., 1978. *Statistics for Experimenters*. Wiley.
- Ciriello, C., 2005. Raglan performance model. Personal Communication, February 2004.
- Cochran, 1946. Relative Accuracy of Systematic Stratified Random Samples for a Certain Class of Populations. J. Iowa Agricultural Experiment Station, Ames, Iowa, Project 891, pp. 164-177.
- Cramer, L.A., 2001. The extractive metallurgy of South Africa's platinum ores. *Journal of Metallurgy*, October 2001, pp. 14-18.
- Fragomeni, D. and Boyd, L., 2003. Grind-Recovery Testwork on Samples of the Raglan End-Members. Falconbridge Report, 6 January 2003.
- Fragomeni, D., Holloway, A., DiFeo, T., Lalonde, S. and Langdon, 2004. The Third Raglan Statistical Benchmark Survey Of November 2003, Mass And Value Balance, Falconbridge Report, April 26, 2004.
- Fragomeni, D., Daoust, D. and Lalonde, S., 2004. Falconbridge Technology Center –Virtual flowsheet for the Raglan Concentrator, Falconbridge Report, Dec 1, 2004.
- Fragomeni, D., Boyd, L., Charland, A., Kormos, L.J., Lotter, N.O. and Potts, G., 2005. The use of end-members from grind-recovery modelling, tonnage prediction and flowsheet development at Raglan. *Canadian Mineral Processors 2005*, Paper No. 5, pp. 75-98.
- Fragomeni, D., Daoust, D. and Lalonde, S., 2005. Phase 2 – Virtual Flowsheet Testwork –Cleaning Circuit Report, Falconbridge Report, March 7, 2005.
- Gy, P.M., 1979. *Sampling of Particulate Materials – Theory and Practice*. Ch. 26.
- Hoffmann, M., 2003. Automated Flotation Cell Evaluation and Conditioning Time Tests, Falconbridge Report, March 27, 2003.
- Lotter, N.O., 1995. A Quality Control Model for the Development of High-Confidence Flotation Test Data. M.Sc.(Eng.)(Chem.) Thesis, University of Cape Town, June 1995.
- Lotter, N.O. and Stickling, J.S., 2000. *Process Mineralogy Standards Manual*. Falconbridge Report, 2000.
- Lotter, N.O., Whittaker, P.J., Kormos, L.J., Stickling, J.S. and Wilkie, G.J., 2002. The development of process mineralogy at Falconbridge Limited, and application to the Raglan Mill. *CIM Bulletin*, Nov/Dec 2002, pp. 85-92.
- Lotter, N.O., Kowal, D.L., Tuzun, M.A., Whittaker, P.J. and Kormos, L.J., 2003. Sampling and flotation testing of Sudbury Basin drill core for process mineralogy modelling. *Minerals Engineering*, 16, pp. 857-864.
- Lotter, N.O. and Laplante, A.R., 2005. Residual effects of lognormality in concentrator data. *Canadian Mineral Processors Conference*, 2005, Paper No. 20, pp. 359-387.
- Lotter, N.O., 2005. *Statistical Benchmark Surveying of Production Concentrators*. Ph.D. (Met. Eng.) Thesis, McGill University, August 2005.
- Langlois, P. et al., 1998. Falconbridge Technology Center – Salient Features of the June 1998 Statistical Benchmark Survey.
- Peters, O. et al., 2004. Falconbridge Technology Center - Flotation Mini Pilot Plant Commissioning Report. Falconbridge Report, August 13, 2004.
- Peters, O. et al., 2004. Falconbridge Technology Center – Flotation Mini Pilot Plant – Raglan Validation Campaign, Falconbridge Report, March 17, 2005.
- Stickling, H.A. and Allen, A., 2000. Mass and Value Balance for the Second Raglan Statistical Benchmark Survey. February 2000, Inter-Office Memo, Noranda/Falconbridge Limited, Falconbridge Technology Center, April 6, 2000.
- Whittaker, P.J., Kormos, L.J. and Charland, A., 2001. Introduction of end-members to the Raglan Mineral Processing Programme. Personal Communication, Falconbridge, 2001.