

FLOTATION CIRCUIT DESIGN FOR ADANAC MOLY CORP USING A GEOMETALLURGICAL APPROACH

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ABSTRACT

This paper describes the design of a molybdenite flotation circuit using FLEET technology applied to kinetics data produced from laboratory flotation testing and distributed across the blocks of a mine plan using a geostatistical approach. The geostatistics assigned the statistical error that arises from having a limited amount of sample testing data to the kinetics estimates of each block of ore in the mine plan. The final design then included a quantification of risk based on the accuracy of the block flotation kinetics and model fitting. The design made reference to the extensive technical reports describing earlier metallurgical test work including some pilot plant work over thirty years ago.

The testing involved conducting MinnovEX Flotation Tests (MFT) to determine the rougher flotation kinetics at the specified reagent conditions and rougher-cleaner tests to determine the change in kinetics resulting from regrind. These flotation kinetics were used within FLEET simulations to create a full-scale flowsheet and plant design including recommended equipment sizes and the forecast of operating results. Measurement of detailed flotation kinetics for a wide range of samples allowed the effect of size of grind and efficiency of classification (i.e. width of size distribution) to be predicted for the whole ore body.

INTRODUCTION

Adanac Moly Corp. proposed to develop a 20,000 ton per day mill to produce high quality molybdenite concentrate from its Ruby Creek resource in north-western British Columbia. It is a relatively clean low grade porphyry-monzonite

occurrence containing minimal quantities of other sulphides such as chalcopyrite, pyrite, sphalerite and galena. Molybdenite occurs mainly as coarse flakes with lesser amounts of finer sized values. An optimum plant design was required to can achieve the predicted operating results, at a known level of risk, while treating the variability inherent in the ore body.

The traditional approach to flotation plant design involves the extensive testing of a single large composite sample or a small number of composite samples that are reputed to represent the ore body. Laboratory tests are conducted to establish a process with potential flowsheets and reagent suites. The process is then confirmed by pilot plant work on a large bulk sample or a few samples. The size of equipment required to achieve a specified throughput, recovery and product grade is then calculated from one of a variety of scale-up models. Since the test work has been extensive, it is accepted as being reasonably precise in predicting results; however during the operation of the resulting plant the design is sometimes found to be inadequate. It is then suspected that the flaw in the design process lies in the samples not being sufficiently representative of the ore body, since using only a single or small number of composite samples does not recognize the variability of the flotation response of the ore, nor does it allow for the lack of ore body representation used in the design. It had not been possible to estimate the risk or error in the expected results.

This paper outlines a design procedure that drew on previously conducted testwork used to develop a suitable process from laboratory and pilot plant work on a few samples of ore. It then continued by testing forty drill core samples by a standard technique that allowed the determination of flotation kinetic parameters for each sample. These parameters were then used with the FLEET software program to scale-up to a plant design with an optimum flowsheet and equipment selection suited to an orebody that was described by an average of all the samples tested. The variability of expected plant results were then examined by applying the plant design to the parameters of each of the samples. The samples were widely spaced across the resource, covered the expected proportions of each of the five major lithologies and had a wide range of molybdenite feed grade. Geostatistical analysis of the flotation kinetics data was conducted by identification of the location of the sample points and comparison with the geological plan of the orebody, together with a mine plan of the blocks to be mined during the proposed life of the mine. The geostatistical analysis estimated kinetics parameters for each block and for the average values of each production year, so that the FLEET program could be used to predict the average flotation results for each production year. The statistical variability of the kinetics of the forty samples was used with the FLEET program to determine the precision of the expected average results of the selected plant design and the risk associated with that prediction.

FLEET SIMULATION SYSTEM

A brief description of FLEET software is a pre-requisite to understanding the whole design approach described in this paper. FLEET simulations were used to investigate the performance of a full-scale flotation plant treating ore represented by the Ruby Creek Project drill core samples with the reagent conditions as tested in the laboratory. FLEET was used in both flowsheet design and equipment size selection. A FLEET system comprises three components (Dobby et al, 2002):

- The Flowsheet,
- The circuit Input parameters, and
- The Dataset

THE FLEET FLOWSHEET

In the FLEET Flowsheet component, the configuration of the circuit and the equipment specifications, e.g. number of cells, type, dimensions, are defined. Various flowsheets are then simulated to determine an optimum.

FLEET INPUT PARAMETERS

The FLEET Input parameters define how the circuit is being operated in terms of stage froth recoveries across individual units (pull-rates), stream % solids (water recoveries across units) and the cleaner circuit modifier factors.

Through a series of FLEET runs, these Input parameters can be manipulated to generate a set of rougher and overall circuit grade and recovery results, which can be plotted as typical grade/recovery curves. This is of particular importance, since industrial circuits do not operate to one specific grade/recovery point, but rather, shift up and down the grade/recovery curve that is dictated by the feed, reagent conditions and the physical configuration of the circuit. Various circuit configurations can be compared by producing the grade/recovery curves generated when each circuit treats the same feed, with the same reagents, but under a range of different operating conditions.

THE FLEET DATASET

The FLEET Dataset defines the feed material entering a flotation circuit in

terms of feed rate (tph), feed grind (P_{80}), head grade and flotation kinetic parameters at that grind. These parameters are a description of each mineral species in terms of:

- the ultimate recovery achievable by true flotation, R_{max} (that is, flotation by attachment only after the contribution from hydraulic entrainment has been deducted)
- the average rate constant, k_{avg} and a measure of the rate constant distribution, alpha.
- R_{max} and k_{avg} are also expressed in terms of any change with respect to a small change in grind, i.e. $R_{max,slope}$ and $k_{avg,slope}$ so that any change in P_{80} can be investigated.

The dataset can be a single line describing the feed to a flotation circuit at one particular time (e.g. a single

were spatially well distributed across the ore body. Molybdenum content as reported from drill core assays on one half of a core section did not always compare well with that determined during the flotation test work on the other half of the core section, probably due to sampling error when splitting the core and in sample preparation of batches for flotation tests. However, there appears to be no bias between the two measures as shown in Figure 1. Note that the higher grade samples (>0.13%Mo) proved harder to sample, possibly due to the presence of large crystals (or rosettes) of molybdenite that are occasionally seen in the drill core. This comparison highlights the sampling difficulties and the potential ore body estimation errors.

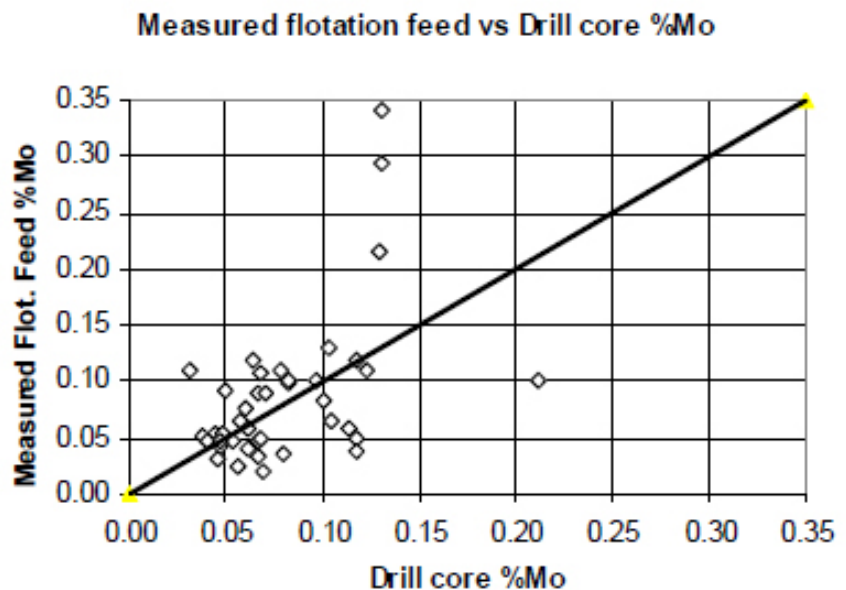


Figure 1: Measured flotation feed %Mo versus drill core assays %Mo

drill core sample), or for a design or production forecasting study, the dataset can comprise tens of thousands of lines, where each line represents a block of ore (of say 4 to 5 hours of production). Through the dataset, the effect of variations in feed rate, feed grind and feed ore characteristics (head grade, flotation kinetics) can be determined.

SAMPLES USED TO DESCRIBE THE ORE BODY

Forty samples were selected for flotation test work that covered the variation in lithology and molybdenite content and

LABORATORY FLOTATION TEST WORK

ROUGHER FLOTATION

The Minnovex Flotation Test, MFT

The objective of the MFT is to measure the pulp kinetics applicable for each drill core sample at the reagent suite tested. The protocol for the MFT is well described in the literature (MinnovEX, 2004). In this case the same flotation conditions were applied to each sample using a standard addition of kerosene as collector and pine oil as frother for a time

that was adequate for recovery of all attached particles.

The grinding time required in the laboratory mill was calculated from Bond work index and feed size distribution to produce a P80 as close as possible to the target P80. In most cases this target was satisfactorily achieved. However, one of the features of the MFT is the ability to quantify the effect of change in flotation feed size and to adjust the results to a consistent size, if required. In this case all resulting kinetics parameters were adjusted to a standard P80 of 210 microns.

Kinetic parameter extraction procedure

Pulp kinetic parameters for each test are derived for each mineral species from the sizing and chemical analyses of the feed, individual concentrates, combined concentrate and tailings samples (Dobby and Savassi, 2005) for use in the FLEET dataset. It is also possible to calculate the effect on the kinetics of changing the feed size distribution, the "m" value of the Rosin-Rammler distribution. It is possible to simulate a feed size distribution similar to that expected in a full-scale operation rather than the narrow distribution produced in typical laboratory mills. In this case the "m" value of the Rosin-Rammler distribution was about 1.0 in the laboratory ball mill, whereas a value of 0.7 to 0.8 may be more likely in a plant distribution containing more slimes and coarse material (typical of single stage plant cycloning where the P80 is 200 microns) while maintaining the P80 at the same value. All of the data was converted to a standard "m" of 0.7 for plant design.

Results

MFT results are reported via a typical recovery (R_{max}) versus particle size graph as shown for one sample in Figure 2. This figure shows the significant effect of particle size on molybdenite recovery and the benefit that would be achieved by narrowing the size distribution of the grind (increasing the "m" value). True flotation of non-sulphide gangue (NSG) only occurs due to attachment to molybdenite; the very low Mo grade of the ore results in very low NSG

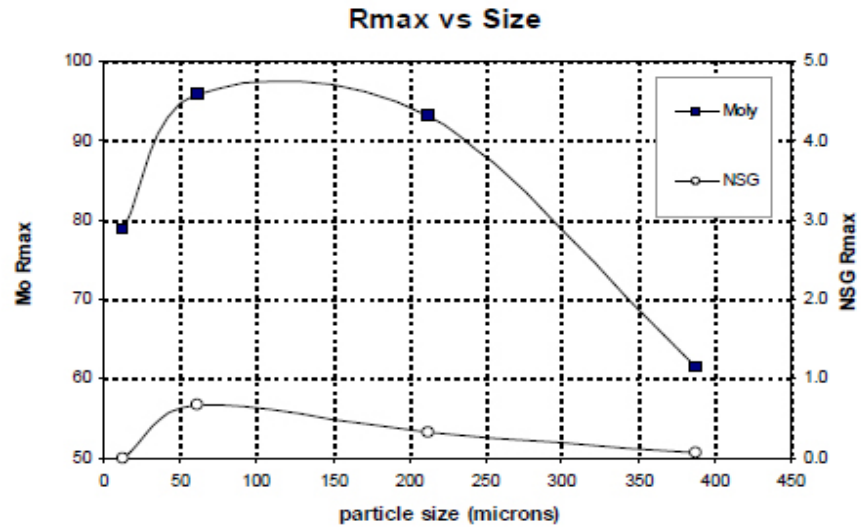


Figure 2: Typical Mo recovery (R_{max}) versus size data

R_{max} values. As a comparison, copper porphyry ore may exhibit NSG R_{max} of 4 to 8%.

The molybdenite recovery was generally poor under the standard size conditions with P_{80} of 210 microns and "m" of 0.7, with an average R_{max} of only 84.8% for the forty samples tested. All the data were recalculated at two further standards: an "m" value of 1.0 ; and a P_{80} of 180 microns. The results are shown in Table 1.

The average Mo R_{max} value increased by almost 5% when changing from "m" value of 0.7 to 1.0, indicating the advantage that would be gained from achieving the narrowest possible size distribution for feed to the flotation circuit. This could be achieved by 2-stage cycloning of mill discharge to minimise the quantity of misplaced coarse material that exits the grinding circuit. Reducing the P_{80} from 210 to 180 microns will improve the average Mo R_{max} by 1.5%. Any decision regarding the change of size can now be made by comparing the cost of the extra grinding against the

Table 1: Summary of kinetics results from the 40 samples.

Grind (microns)	P80= 210	P80= 210	P80= 210	P80= 180	P80= 180	
R-R slope	m= 0.7	m= 1.0	m= 1.0	m= 1.0	m= 1.0	
	Moly	NSG	Moly	NSG	Moly	NSG
Average	84.8	0.6	89.6	0.7	91.1	0.7

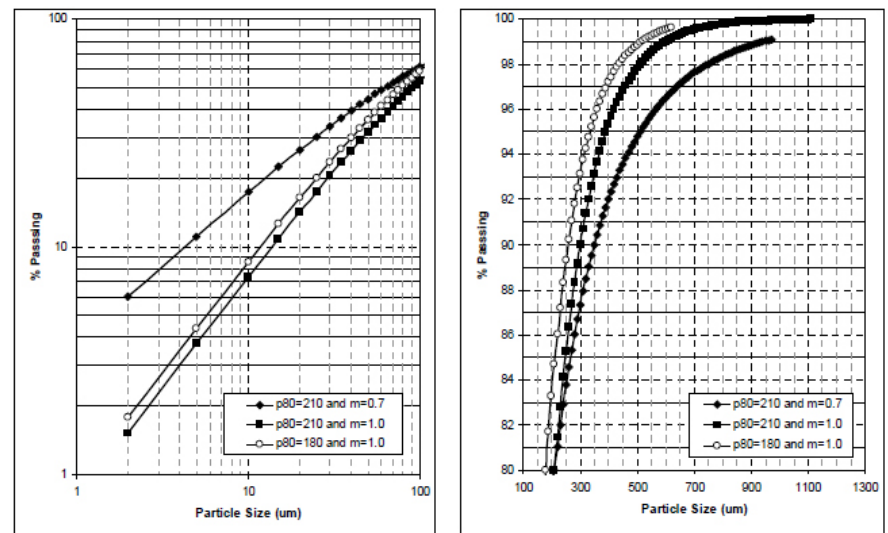


Figure 3: Size distributions at different P_{80} and "m" values.

value of extra recovery.

Examination of the fine and coarse ends of the three size distributions (illustrated as cumulative %passing curves in Figure 3) explains the effect on recovery. The distribution with an “m” value of 0.7 contains considerably more minus 50 and plus 200 micron particles, the sizes where flotation drops off as shown in Figure 2.

The forty samples present a wide range of flotation response under the specified reagent conditions. Mo R_{max} values (at standard at $P_{80} = 210$ microns and “m” = 1.0) sorted by lithology are plotted versus feed grade in Figure 4. The expected dependence of R_{max} on feed grade cannot be observed from these results. There also appears to be no dependence of R_{max} upon lithology. This does not mean that there are no correlations, only that there is too little data and it is too scattered to show the relationships.

Key to the lithology type definitions used in Figure 5:

- CGQM Coarse Grained Quartz Monzonite
- CGQM-T Coarse Grained Quartz Monzonite - transition
- FGQM Fine Grained Quartz Monzonite
- SQMP Sparse Quartz Monzonite Porphyry
- MQMP Mafic Quartz Monzonite Porphyry
- CQMP Crowded Quartz Monzonite Porphyry
- CQMP-T Crowded Quartz Monzonite Porphyry - transition

CLEANER FLOTATION

Rougher-Cleaner test

The MFT conducted on each sample was used to determine the pulp kinetics parameters for each mineral in rougher flotation. Re grind prior to cleaner flotation changes the pulp kinetics; hence the kinetics exhibited by the rougher concentrate are modified (mathematically) prior to feeding the first cleaner. For example, R_{max} of the NSG contained in the ore might be in the neighbourhood of 1%, which could increase to about 50% in the rougher

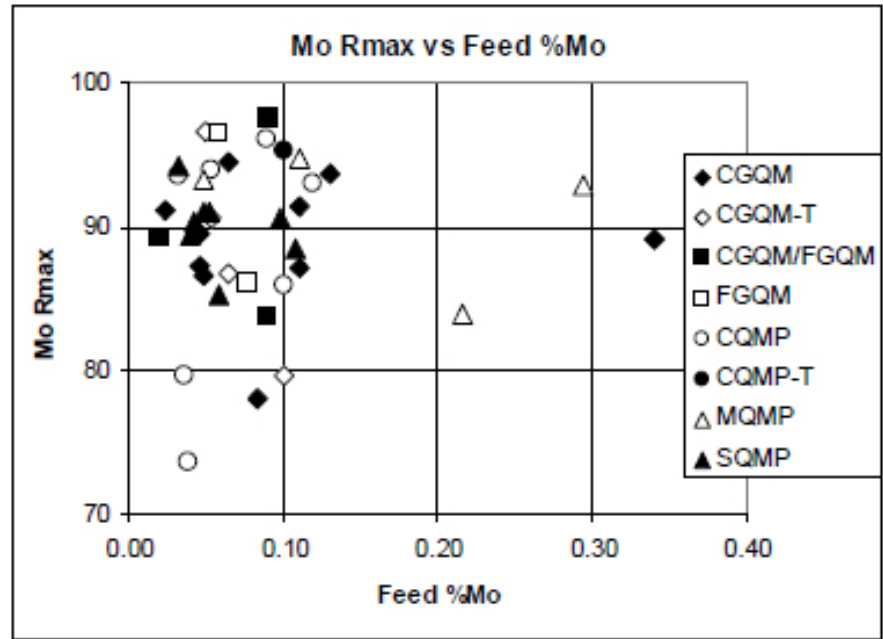


Figure 4: Molybdenite Rmax (standard at P80 = 210 microns and “m” = 1.0) versus feed grade, sorted by lithology

concentrate (with the other 50% being there by hydraulic entrainment); regrind could liberate much of the gangue in this stream and could reduce the NSG R_{max} to say 5% (i.e. modified by a multiplier of 0.1). Therefore the results of the rougher-cleaner tests can be used to estimate the modification so that a complete set of kinetics parameters is available for each mineral that can be applied in the simulation of full-scale plant performance. In this case rougher-cleaner tests were conducted on a selection of samples using a procedure involving 2 stages of regrind and 3 stages of cleaning, as shown in Figure 5. A small addition of kerosene was made to the regrind mills to ensure full molybdenite recovery and sodium hydrosulphide was added to the later cleaner stages as depressant for other sulphides.

Parameter extraction from Rougher-Cleaner tests

The size of the modifier to be applied to the kinetic parameters (typically R_{max} and k_{avg}) for each mineral species (molybdenite and NSG) was estimated by conducting a FLEET simulation of the rougher-cleaner. The simulations were run at Input parameters for froth recoveries and water recoveries that are appropriate for such a test, making allowance for the fact that such recoveries would decline with time along

the banks as the amount of collected material that the operator observed was reduced. The percent solids in the concentrate produced at each stage of the FLEET simulation matched that from the actual test (within reason). Since the model of flotation collection in FLEET considers only true attachment, a further factor for entrainment of mineral species in the froth is included to simulate the total result of the flotation. This factor was estimated at levels that seemed appropriate to the particle size and froth condition at each stage of the process and kept as a constant for all species, in order to simplify the exercise. These FLEET Input parameters were held reasonably constant for all tests, although it is recognized that variations in ore type and grind can result in differences in entrainment factors, and changes in feed grade and rate constants can result in differences in the way that the operator pulls froth from the cell.

Results

The kinetics modifiers established from this exercise for the 1st regrind were as follows:

- 1st Re grind R_{max} multipliers:
- Mo - 1.0 (i.e. no change in the Mo R_{max})
- NSG - 0.05 to 0.3

The R_{max} multiplier of the gangue is dependent upon the amount of gangue

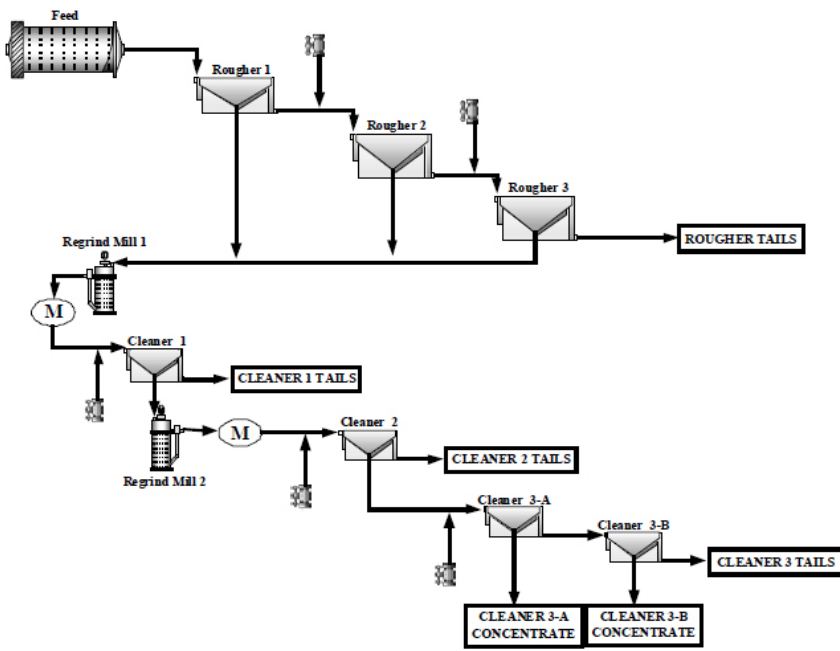


Figure 5: FLEET flowsheet used to simulate laboratory rougher-cleaner tests with a 2 stages of regrind. Note the water addition point, and M (circled) that refers to a modification of the kinetic parameters, in this case as a consequence of the regrind.

that is recovered by true flotation (attached to molybdenite) into the rougher concentrate. The more that the gangue is attached at the rougher feed stage, the more is available for liberation and the lower the multiplier needed for FLEET to account for cleaning as shown in Figure 6, i.e. the less the liberation at the rougher stage, the greater the benefit achieved by the regrind. There is obviously a lower limit for the multiplier and it can be assumed to be in the region of 0.05 to 0.1 (at adequate grind size) for material with higher R_{max} in the feed.

Multipliers for the 2nd regrind established from these tests are in the region:

2nd Re grind R_{max} multipliers:
Mo - 1.0

NSG - 0.05 to 0.4

Again there is a trend that a lower NSG R_{max} multiplier can be used in the 2nd regrind to counter a higher R_{max} multiplier in the 1st regrind (i.e. better liberation in the 2nd regrind if there is more attachment remaining after the first regrind). NSG R_{max} multiplier figures of 0.05 and 0.3 were selected as constant inputs for the 1st and 2nd regrinds respectively for FLEET simulations in the design of a full scale plant.

FLEET SIMULATION RESULTS FOR FULL SCALE PLANT DESIGNS

Average dataset In this design study an 'average dataset' was used to describe the resource as a composite of all the samples tested and simulations were conducted to develop the most suitable flowsheet. After that a 'complete dataset' comprising all the individual samples was produced and run with the preferred flowsheet to see the variation in possible results. The kinetics

parameters of the 'average dataset' are shown in Table 2. This is the dataset for a standard $P_{80} = 210$ microns with 'm' value = 1.0 (i.e. assuming a 2-stage cyclone classification).

Figure 7 illustrates the results (as grade-recovery curves) from several runs using the 'average dataset' and a flowsheet with only 1 regrind but various cleaner

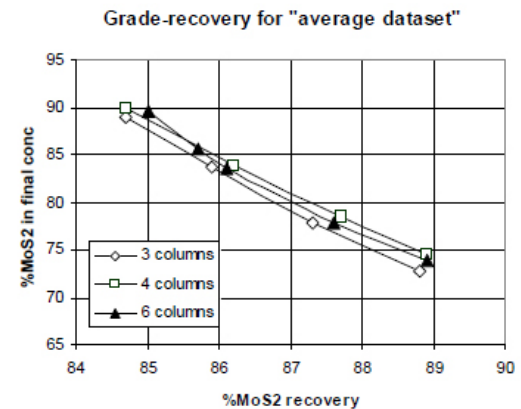


Figure 7: Overall Circuit Grade/Recovery performance with single regrind stages using column cells.

stages using column cells.

The FLEET output suggests that performance can be improved up to a limit of four columns, i.e. five cleaner stages (see Figure 7). The results of multiple stages of cleaning are limited by the extent of the liberation achieved in the regrinding up to the limit of about 85% MoS2 recovery at a concentrate grade of 90% MoS2 (54% Mo) from the average feed grade.

The results of including a 2nd regrind stage with five cleaner stages re shown in the form of grade-recovery relationships compared with performance with only one regrind in Figure 8. Also included in Figure 8 is the recovery benefit determined by FLEET of enlarging the rougher cells from 100m3 to 130m3.

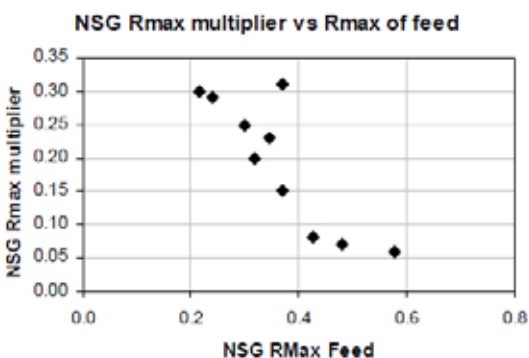


Figure 6: NSG R_{max} multiplier for first regrind vs. NSG R_{max} of feed

Table 2. 'Average dataset' used for the FLEET simulations of the full-scale circuit.

	FEED %	R_{max}	kavg	ALPHA	R_{max} SLOPE
MoS2	0.14	89.6	0.9	6	-0.042
NSG	99.86	1.1	0.25	10	0

Grade-recovery for full-scale plant

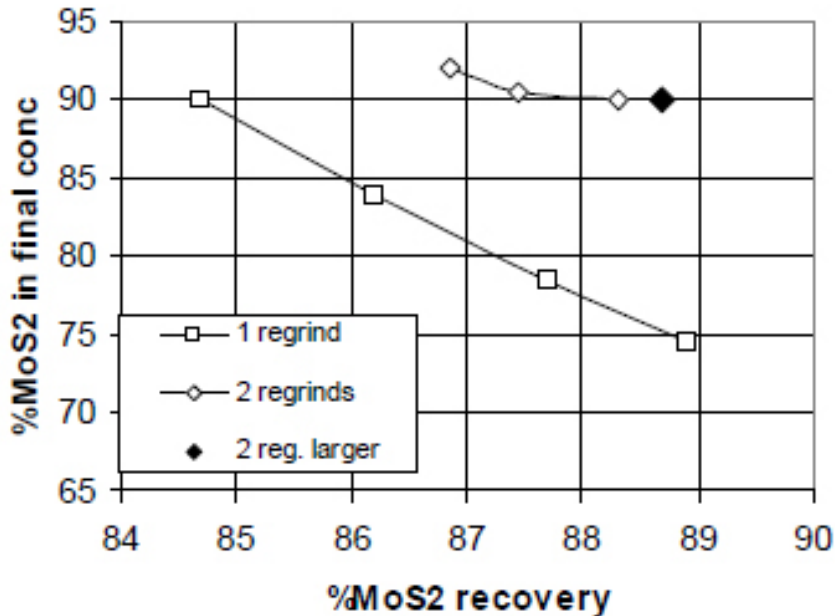


Figure 8: Overall Circuit Grade/Recovery performance for one and two stages of regrind

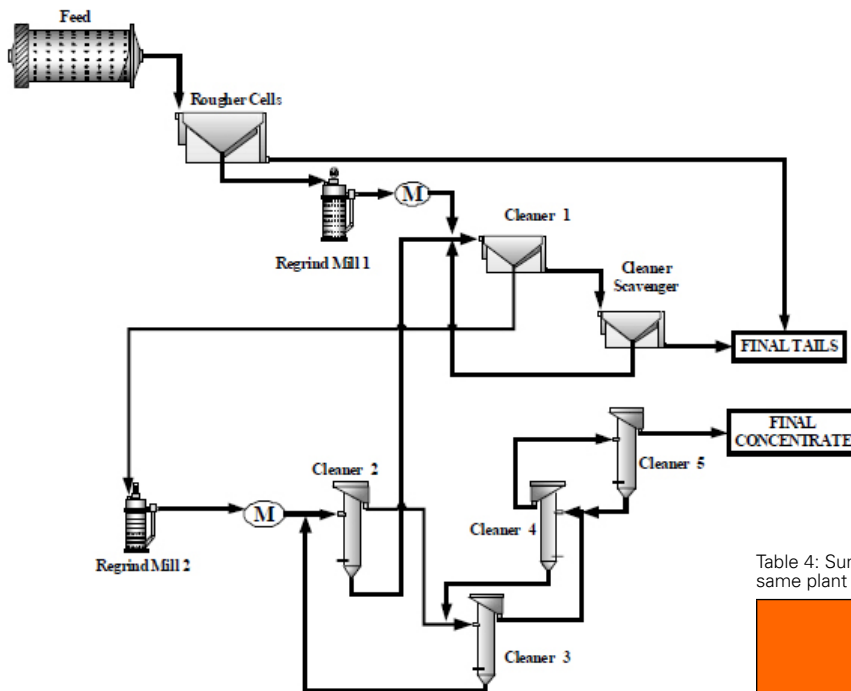


Figure 9: Plant flowsheet with two regrinds and five cleaning stages

The recommended flowsheet shown in Figure 9 includes:

- 8 rougher cells of 130m³ each
- a regrind of the rougher concentrate to P₈₀ = 40 microns
- 5 cleaner cells of 5m³ each
- 5 cleaner-scavenger cells of 5m³ each
- secondary regrind of the 1st cleaner concentrate to P₈₀ = 40 microns
- 4 further stages of columns with diameters decreasing in size (2.2m, 2m, 1.6m and 1.3m) at each stage.

BENEFITS FROM CHANGE IN GRIND

Running the FLEET simulation at the best conditions (illustrated by the single point in Figure 9) with modified 'Average datasets' that correspond to the changes in flotation feed size distribution ("m" value) and grind (P₈₀) (as illustrated in Table 1), produced the changes that might be expected from these new kinetics values, as shown in Table 3.

The benefits of increasing the value of "m" and reducing P₈₀ are apparent.

COMPLETE DATASET OF ALL FORTY SAMPLES

A FLEET simulation using the preferred flowsheet and operating conditions as determined for the 'average dataset' was conducted for all forty samples assuming that they were all ground to a P₈₀ = 210 microns and 'm' value = 1.0 as if each sample represented a separate block of ore being treated in the plant. The results are summarised in Table 4. As would be expected, the large variation in results follows the trend of the variability in Mo R_{max}' which, however, has no relationship to feed grade as seen in Figure 4; in fact the sample with the lowest recovery and concentrate has an average feed grade. Mineralogical examination of that sample indicated the presence of large quantities of chlorite minerals that could be consuming collector and floating as excess slimes. A new reagent suite could be necessary for such ore.

Table 4: Summary of FLEET simulations on all samples under the same plant conditions

	FEED %MOS2	FINAL CONC % MOS2	MO RECOVERY %
Average	0.144	88.2	88.1
Std dev.	0.110	7.6	7.1
Minimum	0.033	54.7	61.6
Maximum	0.568	98.0	96.7

Table 3: Overall Circuit Grade/Recovery performance for the preferred flowsheet on the 'Average dataset' produced at different feed sizes.

P80 MICRONS	m VALUE	MOLY Rmax	NSG Rmax	%MOLY RECOVERY	CONC % MOLY
210	1	89.6	1.1	88.7	90
210	0.7	84.8	0.9	83.9	91.3
180	1	91.1	1.1	90.1	90.1

This exercise demonstrates the power of the FLEET program to handle large amounts of data from the resource. Therefore, geostatistical techniques can be used to distribute flotation kinetics to each block of ore in the mine plan so that they can then be used with FLEET to deploy an array of expected flotation plant results across the plan (Dobby et al, 2004). Mining can then be scheduled by feed grade and expected results to ensure a smooth concentrate production programme.

GEOMETALLURGICAL DISTRIBUTION OF DATA ON THE MINE PLAN

The Mo R_{max} data (with $P_{80} = 210$ microns and 'm' value = 1.0) for the forty samples tested here was subject to a geostatistical study leading to the estimation of flotation response at any block in the mine plan.

Estimation of block values was made using the geostatistical distance weighting method known as Kriging (Preece, 2006) i.e. weighting available sample data according to their distance to the block in such a way that samples close to the block have more influence on the block estimate than other samples further away. The spacing of the samples was adequate for this since at least 75% of the blocks had a sample within 100m. Kriging requires the construction of geostatistical variograms for R_{max} by plotting the semi-variance of differences in the value of pairs of samples of equal distance apart against that distance. The correlogram (i.e. 1 minus the correlation coefficient of pairs of samples) for R_{max} is plotted as a variogram in Figure 10.

The establishment of a model for the variogram allows for the estimation of the R_{max} and the precision of each estimate to be made for each block. The range of influence is determined by the shortest distance apart for pairs having attained the maximum variance. In this study the range for R_{max} values was 100m. The value where the curve cuts the y-axis is referred to as the nugget effect and is a measure of the inherent errors in sampling and measurement of individual data points. In this case

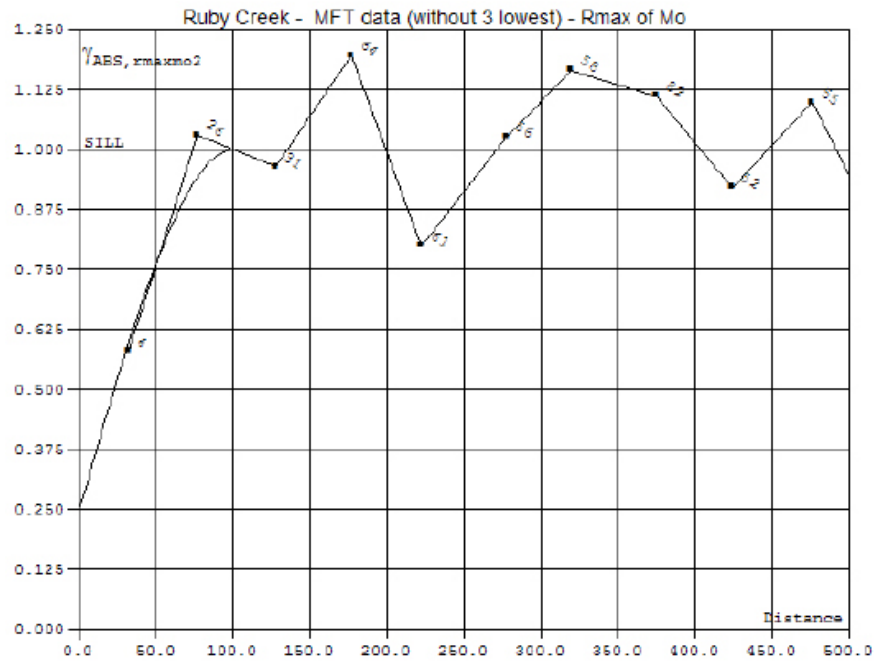


Figure 10: Correlogram (plotted as a variogram) for Mo R_{max}

the relative value of 25% is quite high (reflecting the sampling problems described earlier) and results in a lack of precision in the estimates of block values. In this study, three samples with abnormally low R_{max} values were excluded from the variogram data in order to obtain a reasonable nugget value for the remainder of the ore body. It was assumed that these three had some localised geological effect, e.g. faulting causing increased alteration, that is not typical of the whole ore body.

The samples were identified as six main lithologies further split into a total of eleven sub-types and into three ore types. Statistical analysis indicated no significant R_{max} differences could be determined between types; hence a single variogram was developed for all samples so that a block of any one type was interpolated using samples from any other type.

Since we have no determined correlation of R_{max} with %Mo grade, the %Mo grade estimated in each block could not be used to improve the estimation of the R_{max} of Mo for that block (with some form of co-Kriging).

The resultant standard error (uncertainty) in the estimate of R_{max} is very high at about 5% for all mine blocks, since the nugget effect is high and the samples were widely distributed with no

concentration within any specific area. There is 95% confidence that Mo R_{max} of a block will lie within ± 2 standard errors of the best estimated value. Since the Mo R_{max} for most blocks is in the region of 90% and one standard error is typically 5%, the Mo R_{max} of any block lies somewhere between 80 and 100%. This situation is untenable for production planning and more flotation tests are necessary for mill feed that is expected in the first operating years to improve the prediction.

Since blocks have been identified by year on the mining plan, the geostatistical analysis also allows the determination of annual average grindability values and their precision by the same Kriging technique, making it possible to predict the throughput in each production year. It is also possible to extend the analysis to calculate how many more samples need to be tested from within the range of the blocks mined in a production year in order to improve the precision to any desired level.

The average Mo R_{max} for the blocks in each year of the mining plan are plotted in Figure 11. The results indicate a possible period of low R_{max} at about 88% for the first 2 years, rising to about 90% from the fourth year onwards. This is because the samples that exhibited lower R_{max} values are in the area of the pit that is to be mined in the early years.

Possibly this is a mineralogical effect; perhaps an occurrence of molybdenum oxides or high alteration in the near-to-surface ore. It must be remembered that there is also an uncertainty in the average annual data (that is lower than the uncertainty for individual blocks, due to the greater number of samples used in calculating average data), so the change with time may be more or less than it appears from Figure 11. However, this confirms that more flotation tests should be conducted on mill feed that lies within the first operating years to refine expectations before plant start up.

of the statistical error in the projected results is of value in estimating the associated risks of not collecting more data. A best estimation of the average results for life-of-mine has been based on single tests on forty samples selected to cover a wide range of locations within the resource, the lithology and feed grade. No correlation could be found between maximum achievable molybdenite recovery ($Mo R_{max}$) and lithology or feed grade. Perhaps this is not surprising given the sampling problems of such low grade ore (as illustrated in Figure 1) when the

to determine the potential error in that "best estimate". The statistical variability of flotation kinetics (at a standard grind of $P_{80} = 210$ microns and 'm' value = 1.0) are presented in Table 5. Table 5 includes the results of FLEET simulations using kinetics parameters for the 'average dataset' and those at the 95% confidence limits about the average (mean) i.e. ± 2 standard errors.

Definitions of items in the table:

- 95% of the sample data falls within ± 2 standard deviations.
- Standard error of the mean = Standard deviation of the samples / Square root of the number of samples
- There is a 95% confidence that the true value of the mean falls with ± 2 standard errors of the best estimate for the 'average dataset', i.e. within the range of minimum to maximum in the table.

The FLEET simulations show a 95% confidence that the results will be within 2% of the 'best estimate' recovery and about 1.5% of the concentrate grade. This uncertainty, although large, should be considered in perspective and compared with the larger uncertainties in ore grade and metal prices (Kosick, Bennett and Dobby, 2002).

The precision could be improved by:

- Checking some of the outlier values for measurement errors by repeat tests on these samples or others from nearby.
- Conducting tests on more samples to reduce the standard error.

The risk of realising the 'minimum' estimated recovery cannot be significantly compensated by change in the plant design since it is a function of the minimum estimated R_{max} and only about 1% below that value.

CONCLUSIONS

A flotation circuit has been designed by a geometallurgical approach that incorporates a metallurgical design using the FLEET computer software package with a geostatistical analysis of the sample data and ore body. The steps to achieving a design with a quantified risk attached to the results were:

- Refer to previous testwork that

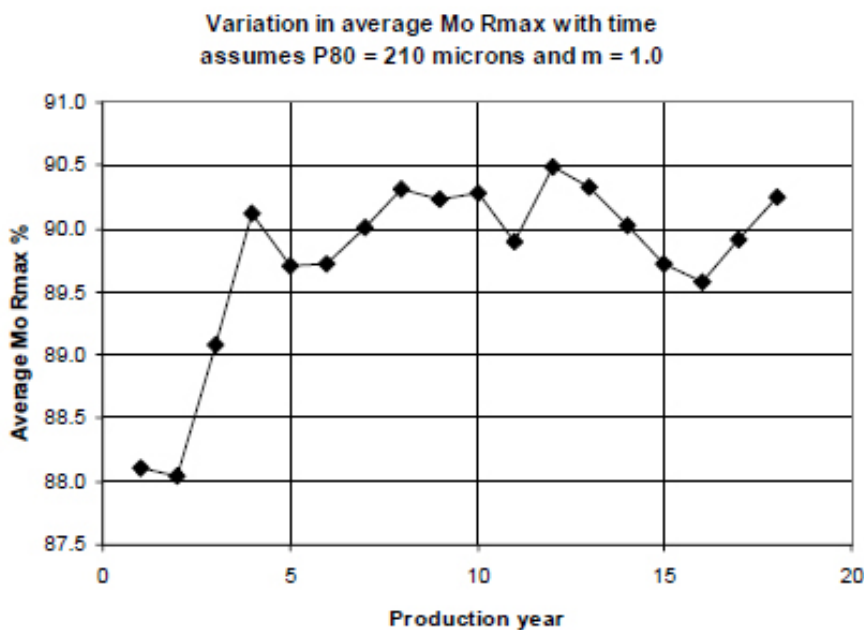


Figure 11: Variation in average Mo Rmax with time

PRECISION ESTIMATION ON AVERAGE RESULTS FOR LIFE-OF-MINE

Potential sources of errors in the projected flotation plant results arise (Bulled and McInnes, 2005) from:

- Unrepresentative samples of ore
- Insufficient ore sampling and testing
- Flotation testing errors: operation, sampling and assaying
- Inaccuracies in kinetics parameter extraction and FLEET modeling

All of these errors can be reduced by more sampling and testing but there is always a practical limit in time and cost in producing a design for a feasibility study. Therefore, having an estimate

molybdenite occurs in fairly coarse flakes. In such circumstances the flotation test itself may have an error of more than $\pm 2\%$ of the recovery value (in fact it was noted during the testwork that batches of feed to duplicate rougher tests varied in grade by $\pm 5\%$). Checks were not run on any results that appear to be abnormal (outliers) nor were any samples that had poor results discarded from the analysis.

Since there was no geostatistical evidence to the contrary, the results from the forty samples were accepted as a valid and representative sample of the resource. As such, the feed grade and average kinetics values used in the FLEET study were a "best estimate" of the resource for predicting plant results and the variability of the kinetics from sample to sample can be used

Table 5: Statistical variability of kinetics and expected plant results

	MOLY R _{max}	MOLY k _{av}	NSG R _{max}	NSG k _{av}	%MOLY RECOVERY	CONC % MOLY
'Average dataset'	89.6	0.9	1.1	0.25	88.7	90.0
Standard deviation of samples	5.4	0.3	1.0	0.14		
Standard error of mean	0.9	0.05	0.15	0.02		
Range of mean - minimum	87.8	0.8	0.8	0.21	86.6	88.4
Range of mean - maximum	91.4	1.0	1.1	0.29	90.7	91.9

established a recommended grind, reagent suit and flowsheet.

- Select forty samples that were geographically spread over the ore body and represent the variability in lithology and feed grade.
- Conduct standardized rougher flotation tests on each of these samples and extract kinetics parameters for each mineral species (molybdenite and gangue) that were used in scale-up calculations by the FLEET program.
- Conduct rougher-cleaner flotation tests on several samples to determine the regrinding needed to achieve specified concentrate grade and the numerical modifiers to kinetics parameters that allowed the effect of cleaner flotation to be described in the FLEET program.
- With an average dataset for the forty sets of parameters, use FLEET to investigate flotation circuit flowsheets and equipment sizing to achieve optimum results at a grind P_{80} of 210 microns with an "m" value for the Rosin-Rammler size distribution of 1.0 for the ore body as a whole.
- Examine the change in results that arise from changes to P_{80} and "m" in the average dataset.
- Examine the variability of the results from using this plant design by applying it to the kinetics parameters from each of the forty samples.
- Use the location of the sample points and the geological and mining plans of the ore body to conduct a geostatistical analysis that estimated grindability values for each mine block and production year with a technique that allowed the determination of the precision of the estimates.
- Predict the throughput for this plant design in each production year using the average kinetics parameters for that year.

- Use the variability of the sample kinetics to determine the precision of the predicted average plant results for the ore body as a whole.

Simulation using an 'average dataset' with feed grade of 0.086%Mo (0.14%MoS₂) produced an overall plant recovery of 88.7% at a final concentrate grade of 90% MoS₂ from an average at a grind P_{80} = 210 microns with "m" value = 1.0. The recovery increases to 90.1% at P_{80} = 180 microns.

The width of the size distribution curve of flotation feed ("m" value) significantly affects the recovery in rougher flotation and must be considered when the grinding circuit is designed. A change from "m" value of 1.0 to 0.7 (typical for some plants with single stage cyclone classification at P_{80} = 210 microns) reduces the estimated plant recovery by almost 5%. Hence a 2-stage cyclone classification system is recommended for the grinding circuit.

The geostatistical study indicated that:

- The samples were well spaced around the resource for best representation.
- There was no correlation between Mo R_{max} and feed grade or lithology. Some of the variability may be due to sampling error because of the low grade "nuggety" material. None of the data has been checked by duplicate sampling and testing.
- The Mo R_{max} values have limited spatial correlation; there is a big nugget effect, meaning that a best estimate of the value for any block can be made from the values of the nearest samples, but the precision of that estimate is very low.
- There is an indication that the average Mo R_{max} for blocks mined during the

first two years will be about 2% lower than average for the resource as a whole. The precision of this estimate should be improved by testing more samples from this period since there will be an impact on expected metal recovery and project economics.

It is estimated that the expected average life-of-mine results are accurate to +/- 2% in terms of recovery and +/-1.5% in terms of grade at a 95% confidence level, i.e. there is a 2.5% risk that the results will be worse than the lower limit. Enlargement of the plant will not compensate for the possibility of lower recovery since the uncertainty lies in the average value for Mo R_{max}. The precision can be improved and the risk reduced by further tests to check some of the existing data and add more information.

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