

THE BEHAVIOUR OF GOLD IN HEMLO MINES LTD. GRINDING CIRCUIT

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ABSTRACT

This paper compares the behaviour of gold and ore in the grinding circuit of Hemlo Mines Ltd. Particular attention is given to grinding kinetics, classification behaviour, and liberation. For grinding kinetics, laboratory grinding of gold flakes and silica, 840-1200 μm in size (14/20 mesh), was also performed to provide a standard for comparison and to study in a controlled environment the mechanisms of breakage, folding, smearing and impacting.

Grinding kinetics were characterized at laboratory scale with breakage and selection functions. The breakage function showed that 75% of gold disappearing from the 840-1200 μm class reported to the 600-840 μm ; this figure is much higher than for silica (46%) or most other minerals, and implies that comparatively fewer fine fragments are produced from the breakage of gold flakes, on account of gold's malleability. The selection function of silica was four times that of gold. At plant scale, the ratio of the selection function of ore and gold increased from 6 for at 50- 100 μm to 20 at 500-1000 μm .

Observation of original flakes and their fragments with the scanning electron microscope showed that the main mechanism of "grinding" from the 840-1200 μm to the 600-840 μm class was folding rather than actual breakage. This was confirmed by a measure of individual flake weight. The postulated breakage cycle is that relatively globular flakes become increasingly serrated through grinding; they can then regain their original shape through folding and re-flattening into cylindrical and spherical shapes, as the majority does; however, some fragments will at this point undergo actual breakage. Photographic evidence is presented to support the proposed mechanisms.

Smearing of gold onto silica was observed when silica was ground after a gold, and embedding of silica into gold flakes when gold was ground after a silica. Both mechanisms occur whenever gold and harder minerals are jointly ground, and result in "unliberation" of gold. It is postulated that smearing of gold onto other minerals plays an important role in explaining how gravity recovery can increase overall gold metallurgy, especially when used ahead of flotation.

Classification of gold in the primary hydrocyclones takes place at a much finer cut-size than ore, 20 vs. 57 μm . This and the slower grinding kinetics result in high gold circulating loads in the primary loop, 6700%, and a gold content in the primary cyclone underflow (PCUF) is twenty four times that of the ore. The gold size distribution for primary cyclone overflow is much finer than that of the ore, although they are essentially similar in the PCUF.

Liberation, or more accurately "gravity recoverability", was assessed with a 7.5 cm (3") Knelson concentrator. It varied between the thirties for the primary mill discharge and two cyclone overflows, to highs of 89 and 92% for the PCUF and secondary mill discharge, 89 and 92%, respectively.

INTRODUCTION

Gold's behaviour in grinding circuits is of particular interest. First, it is so different from that of other minerals that it accumulates in grinding circuits, which can result in losses due to overgrinding, difficulties in estimating head grade or gold inventory, and a security risk. If, on the other hand, the use of gravity recovery is elected to alleviate these problems, an enlightened choice does require knowledge of gold's behaviour, in order to select the appropriate recovery location and unit, and predict gold recovery as accurately as possible. In fact, the accurate prediction of gold recovery by gravity and ultimately of improvements in overall recovery is a critical part of the decision-making process when gravity circuits are contemplated. Often, this decision is made at the plant design stage, on the basis of simple amalgamation tests. If existing methodologies to assess the appropriateness of gold gravity circuits are to be improved, gold's behaviour in grinding and gravity circuits is at the core of the required knowledge.

Gold's distinct behaviour in grinding circuits is dictated by its malleability and density, which affect all important mechanisms: breakage, classification and liberation. These, in turn, will affect gold's residence time in the grinding circuit and recoverability by gravity. These mechanisms are traditionally described for overall ore, occasionally for specific mineral species. Grinding is normally represented as first order kinetics, with a rate constant often termed the selection function (Epstein, 1947; Reid, 1965). Breakage is defined as disappearance from a given Tyler size class (interclass breakage is neglected), with the breakage function, b_{ij} , the mass fraction breaking from size class i into size class j . Classification is defined by classification efficiency, or Tromp curves, relating the fraction reporting to the underflow; one parameter, the D_{50} (or cut-size), is mineral specific. Liberation is normally determined by image analysis or dense liquids, although amalgamation is the accepted technique for gold.

Previous work on gold's behaviour in grinding circuits is limited. High circulating loads are often reported, but formal measurements of parameters governing grinding or classification are virtually non-existent. One study (Laplante et al., 1990) reports a classification efficiency much higher than that of the host ore, but characterization of the size behaviour stops at 37 μm . One South African study focuses particle morphology and reports spherical and cylindrical shapes (Hallbauer and Joughn, 1973).

Two technical problems associated with study of free gold are statistical representativity of small samples ("the nugget effect") and the evaluation of "free gold" content. A traditional solution to both problems is to contact representative sample, typically 5 kg, with mercury to amalgamate the gold, and assay the mercury for gold content. Although this method offers a reproducible and reliable estimate of free gold content, it suffers from significant limitations. First, size-by-size information is lost; second, amalgamability is not equivalent to recoverability by gravity; and third, the use of mercury constitutes a health and environmental hazard. In a recent test program, the use of a Mozley Laboratory Separator on single size classes was tested (Liu, 1989; Laplante et al., 1990); although gold recovery showed a definite correlation with liberation and results gave a clear indication of unit performance, the approach proved time intensive and was not fully reproducible. It did demonstrate, however, the high efficiency of 75

cm (30") and 19 cm (7.5") Knelson concentrators (Knelson, 1985) in recovering free gold. The advent of a portable 7.5 cm (3") Knelson capable of processing small samples now provides an alternative to amalgamation. Samples of comparable size (5-20 kg) can be processed, but the concentrate, generally 100 g in mass, retains its own particle size, and gold particles retain their own identity (grade, size, weight and morphology). Limited test work (Banisi, 1990) has shown that the Knelson yields results very comparable to amalgamation. In this work, a case study is presented to illustrate the use of a 7.5 cm Knelson for plant studies.

EXPERIMENTAL PROCEDURE

Laboratory Work

The laboratory work was aimed at estimating the breakage and selection function of gold. Grinding a single Tyler size class for various incremental times is a frequent approach (Herbst and Fuerstenau, 1968; Hodouin et al., 1978), which was retained for this work. Over 1000 flakes of 840-1200 μm gold flakes (approximately 5 g) from the gravity circuit of Les Mines Camchib Inc. were first acid washed sequentially in hydrochloric and nitric acid, with intermediate water rinsing; this procedure was aimed at removing impurities from the surface, as well as identifying flakes other than gold (tramp copper and steel); once all flakes other than gold had been removed, fifteen of the more suspicious remaining flakes were examined with a Jeol scanning electron microscope (SEM) and were found to be gold. All flakes were ground in a porcelain mill (20 cm long, 23 cm in diameter) with 6.1 kg of 2.4-2.6 cm balls, for times of 0 to 210 s. Individual flakes from the original and were weighed after each incremental grinding time, to study the evolution of particle weight; individual flakes were also examined with the SEM and photographed. To serve as a basis for comparison, a 50 g sample of silica sand from Indusmin Ltd. was ground incrementally before the gold sample, as was a similar 25 g sample after.

Plant Work

The Hemlo mill is located about 25 km east of Marathon, Ontario (Larsen and Tessier, 1986). At the time of the study, the milling rate was 3000 t/d; the grinding circuit, shown in Figure 1, is comprised of three ball mills and two cyclone stages. The second and third mills are operated in series, each in closed circuit with a cyclopalc. In August of 1988, a thorough sampling campaign of the grinding circuit was performed. All streams shown in Figure 1 were sampled for two hours, with 15 minute sample increments; the primary mill discharge (PMD), primary cyclone underflow (PCUF), secondary mill discharge (SMD), and secondary cyclone underflow (SCUF) yielded dual samples, and the primary cyclone overflow (PCOF), secondary tertiary mill discharge (TMD), cyclone overflow (SCOF) and secondary cyclone underflow (SCUF) single samples. Samples were weighed wet, dried, sub-sampled for gold assaying, and the remainder screened at 10 mesh to yield feed for a 7.5 cm (3") Knelson concentrator. All samples, between 6 and 13 kg in weight, were processed with a 7.5 cm Knelson concentrator at a feed rate of 750 g/min, at back-water pressures of 42-50 kPa (4.5-5.0 psi). Concentrates, 90

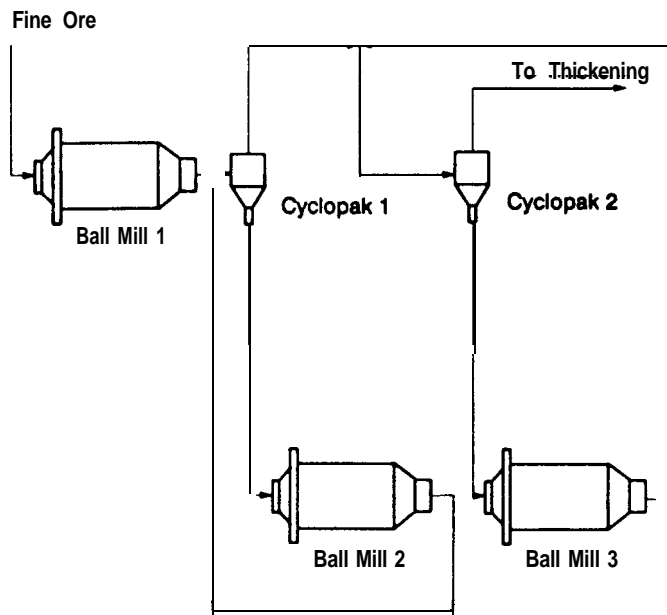


Figure 1 Grinding Circuit at the Golden Giant Mill

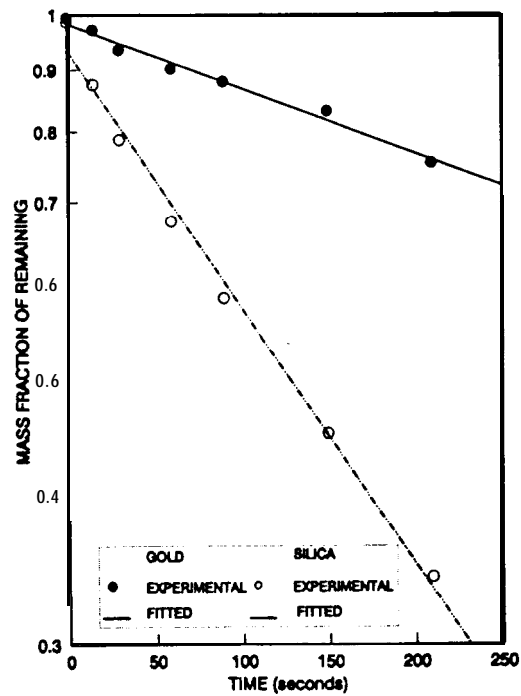


Figure 2 Mass Fraction Remaining in the 840-1200 μm as a Function of Time for Gold (5 g) and Silica (50 g)

to **130 g** in weight, were screened at 37 to 1200 μm , and each class assayed for gold content. Representative samples of the Knelson tails were also screened and assayed. Samples of the -37 μm (approximately 1-2 g for concentrates and 15 g for tails) were screened at 25 and 15 μm , and each fraction assayed for gold. All gold analyses were by fire assay at the Golden Giant Mine Laboratory. All size analyses and gold assays were adjusted with the NORBAL2 software (Spring, 1986).

RESULTS AND DISCUSSION

Laboratory

Figure 2 shows the mass fraction remaining in the 840-1200 μm for gold and the 50 g silica sample. The linear relationship on the vertical logarithmic scale shows that grinding follows first order kinetics, both for gold and silica. The slope of the two lines is the rate constant, the selection function; clearly, that of gold, 0.0017 min^{-1} , is much lower than that of silica, 0.0063 min^{-1} . The difference is in fact even larger, as the lower weight of gold favours its grinding; when the weight of silica is reduced from 50 to 25 g, its selection function increases to 0.0074 min^{-1} , more than fourfold that of gold.

The rate of appearance of ground material in the size classes immediately finer than the “mother” size class can be used to estimate the breakage function of a material. Herbst and Fuerstenau (1968) proposed that the cumulative breakage function could be estimated from the following equation:

$$\ln[1 - Y_i(t)] = - B_{i1} S_1 t \quad (1)$$

where $Y_i(t)$: weight fraction finer than size i
 B_{i1} : weight fraction of material finer than size class i when broken from size class 1 (840-1200 μm)
 S_1 : selection function of size class 1, in s^{-1}
 t : time (s)

To estimate B_{i1} , a simple linear regression of $\ln[1 - Y_i(t)]$ against time is performed, and the slope, $B_{i1} S_1$, is divided by S_1 . The breakage function, b_{ij} , is equal to $B_{i-1,1} - B_{i1}$. For the finer size classes, $Y_i(t)$ cannot be measured accurately, and the cumulative breakage function, B_{i1} , can be estimated from (Austin and Luckie, 1971/72a and b):

$$B_{i1} = Q_1 R^\alpha + (1-Q_1) R^\beta \quad (2)$$

where Q_1, α, β : parameters of the model
 R : ratio of the lower size limits for size class i and 1

The parameters of Eq. 2 are estimated from the measured breakage function of the coarser classes, Table 1 compares the breakage function of gold and silica. The high fraction of gold reporting to the size class immediately finer than the original size class is very high, 0.747, compared to that of silica, 0.458. As a result, comparatively less finer gold is produced; only 13.0% is finer than 300 μm (50 mesh), compared to 25.3% for silica. This has direct incidence on required grinding time, as comparatively more breakage events will be required to grind gold down to a specific particle size.

Table 1 Breakage Function for Gold and Silica for the 840-1200 μm
(Weight fraction reporting to each finer size class)

Size class (μm)	Gold	Silica
600-850	0.747	0.458
420-600	0.082	0.173
300-420	0.041	0.116
210-300	0.037	0.075
150-210	0.027	0.050
105-150	0.021	0.039
75-105	0.012	0.034
53-75	0.009	0.017
37-53	0.008	0.011

After each grinding time, particles from the original class and the next three finer size classes were weighted. Although individual particle weight in any size class was found to vary significantly, grinding time was found to have no significant and consistent effect on average weight. Table 2 presents the average weight of the four coarsest classes, as well as the ratio of the average weight in the original class to that of the next three finest ones. The theoretical ratio is also given using the assumption that particles are geometrically similar (case 1) and that flake thickness is constant (case 2). It must be recognized that if the actual weight ratio is lower than that predicted by case 1, average flake thickness increases upon grinding in finer classes (folding). If the measured ratio is intermediate between the two cases, flakes are losing their "flakiness" as they are ground into finer classes (the ratio of flake thickness to diameter is increasing). Finally, a measured ratio greater than that of case 2 would imply that particles are getting "flakier" upon grinding into finer size classes --an unlikely event.

Table 2 Average Weights of Gold Flakes and Analysis
of the Average Weight ratios
(weight in 840-1200 μm /weight in finer classes)

Particle Size (μm)	Average Weight (mg)	Ratio of weight (initial/fragment)	Ratio predicted by constant thickness	Ratio predicted by constant shape
840- 1200	4.87		Case 1	Case 2
600-840	3.10	1.57	2.00	2.83
420-600	1.30	3.75	4.00	8.00
300-420	0.51	9.55	8.00	22.6

Results show the evidence of significant folding from the 840-1200 to 600-840 μm size class, as the measured weight ratio, 1.6, is lower than that predicted assuming constant thickness, 2.0. The second fragment class, 420-600 μm , also shows evidence of folding, with a measured weight ratio of 3.8 (4.0 for constant thickness). The third fragment class, 300-420 μm , has flakes of thickness slightly lower than the 850-1200 μm , as the measured weight ratio, 9.4, is intermediate to those of cases 1 and 2, 8.0 and 23.

Examination of individual flakes also confirms widespread folding. First, a phenomenon of "aging" is apparent, with relatively globular (young) flakes (Figure 3) acquiring increasingly irregular edges, to "middle-age" (Figure 4) and finally "old-age" (Figure 5). However, the aging process can be reversed by folding, either into a cylindrical particle (Figures 6 to 8), or a sphere (Figures 9 to 11). This is in good agreement with Hallbauer and Joughn (1973). The folding process generally takes place with either young or middle-age particles; beyond a certain point, a particle becomes too irregular in shape and some breakage must take place.

Embedding of silica particles into softer gold particles was repeatedly observed (see Figs. 3 to 11). As the flakes were relatively clean prior to grinding, it is likely that most silica fragments were impacted during the laboratory grinding, with residual silica coating the grinding ball and inside of the mill. A similar phenomenon was observed when grinding silica subsequent to the grinding of gold, as significant gold was detected in the surface of the ground silica. It can be postulated that the grinding medium acts as a "catalyst" to favour the interaction between gold and other minerals. Hard mineral particles encrusted onto balls are dislodged into gold flakes upon impact; similarly, gold smeared on grinding balls is scoured as mineral particles impact the balls.

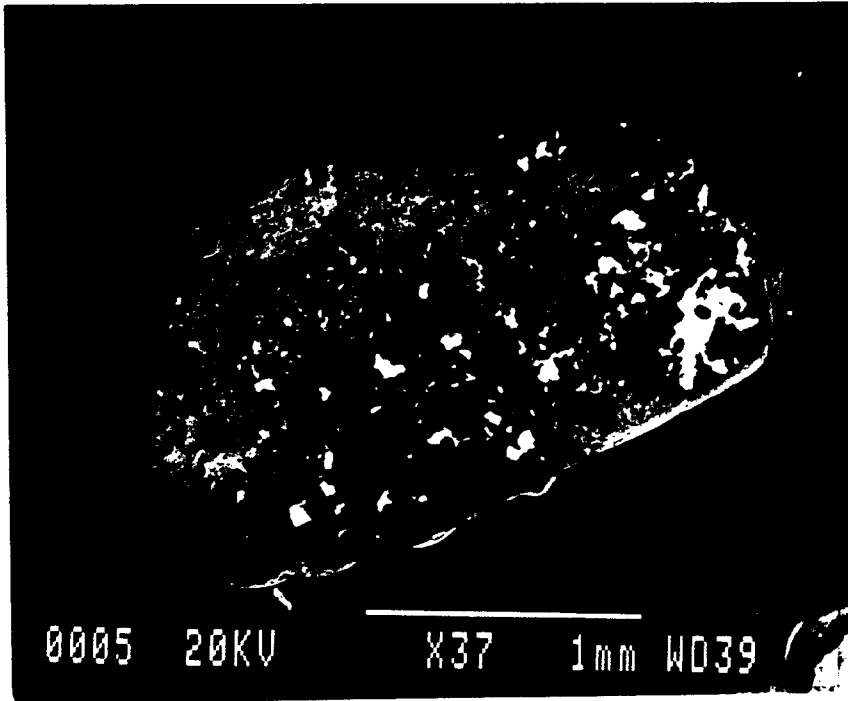


Figure 3 Photo of a "Young" Flake

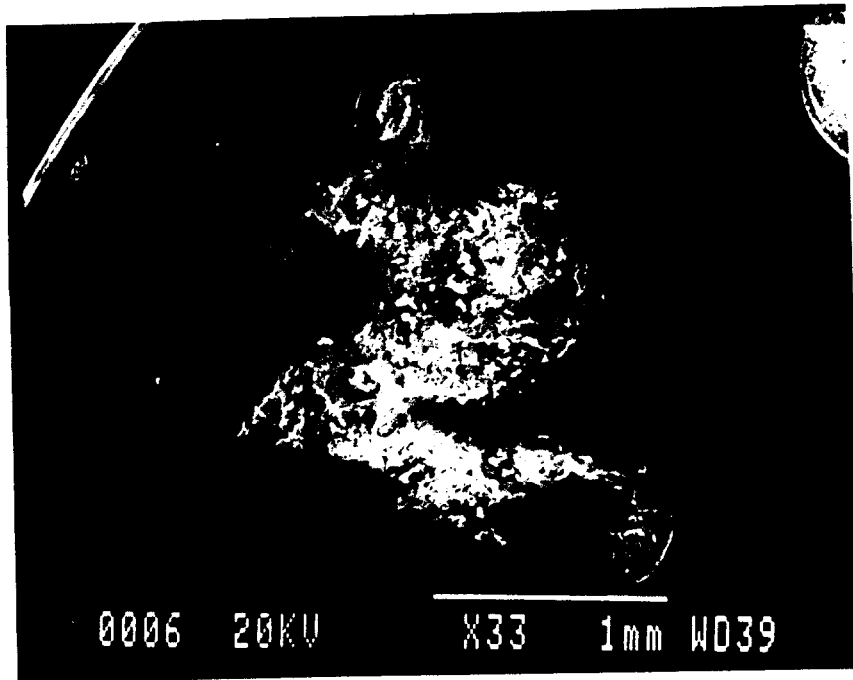


Figure 4 Photo of a "Middle-Age" Flake

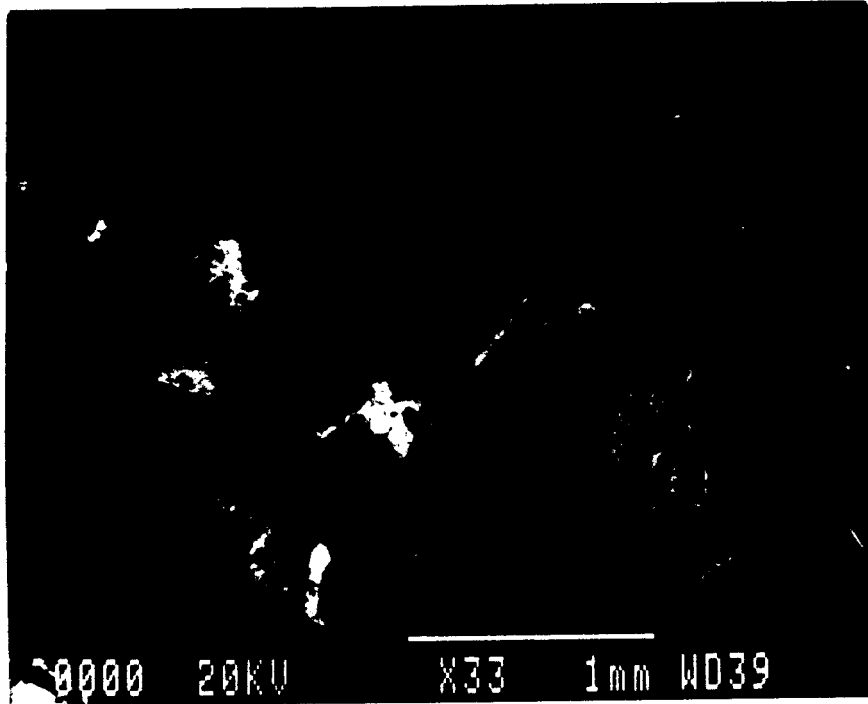


Figure 5 Photo of a "Old" Flake

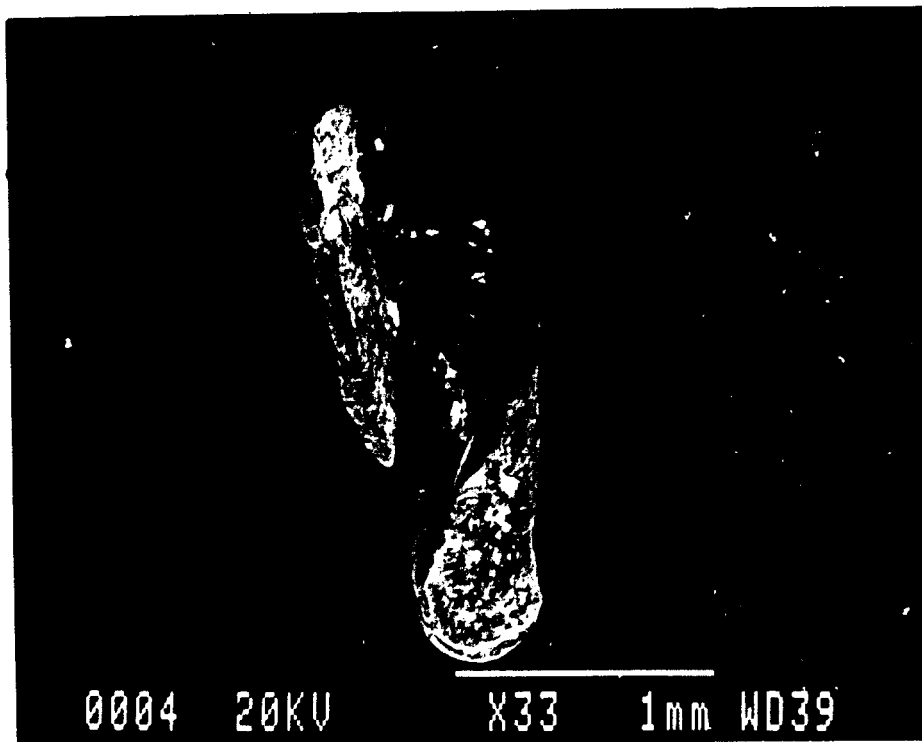


Figure 6 Initial Stage of the Folding of a Gold Flake in a Cylindrical Shape

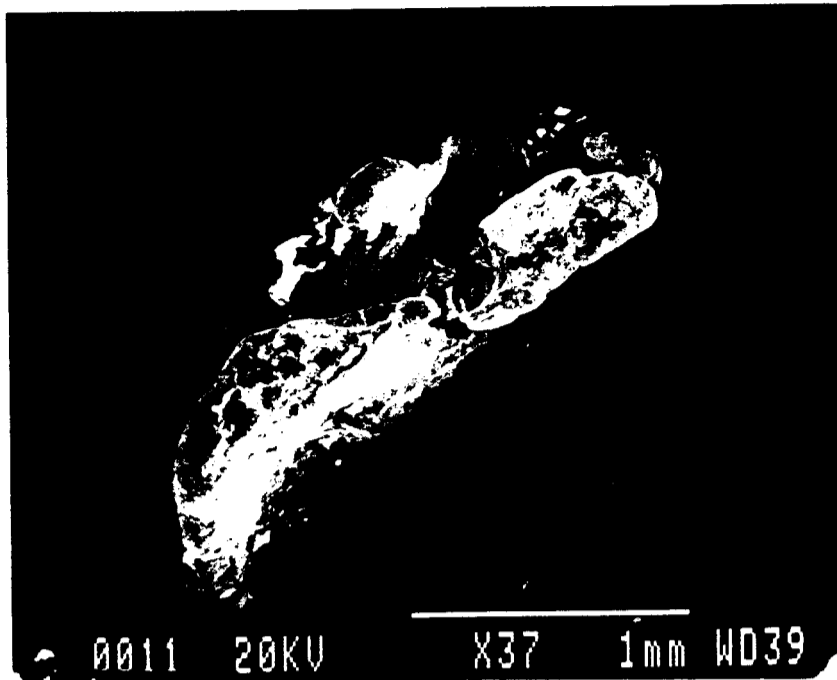


Figure 7 Intermediate Stage of the Folding of a Gold Flake in a Cylindrical Shape

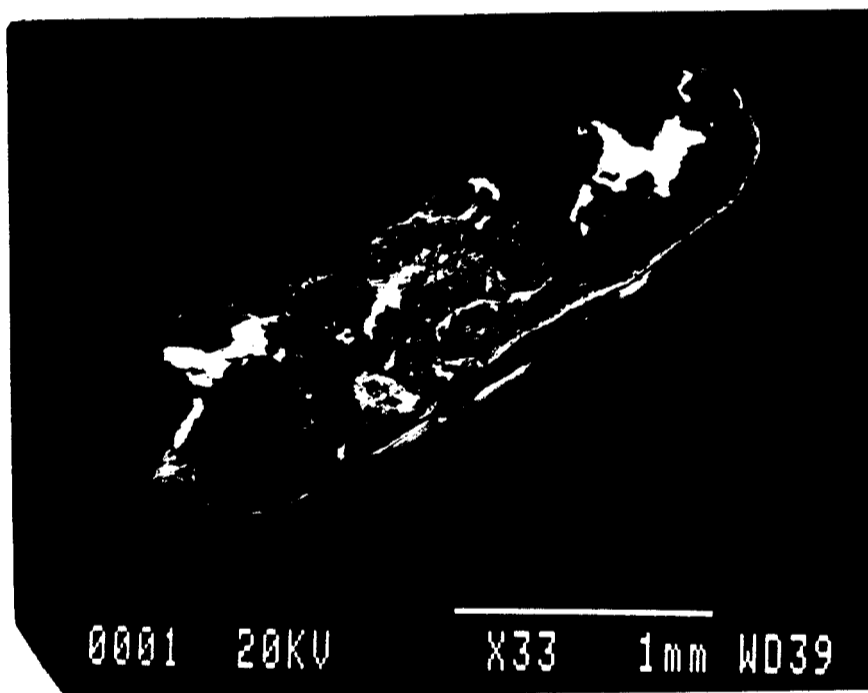


Figure 8 Final Stage of the Folding of a Gold Flake in a Cylindrical Shape



Figure 9 Initial Stage of the Folding of a Gold Flake in a Spherical Shape

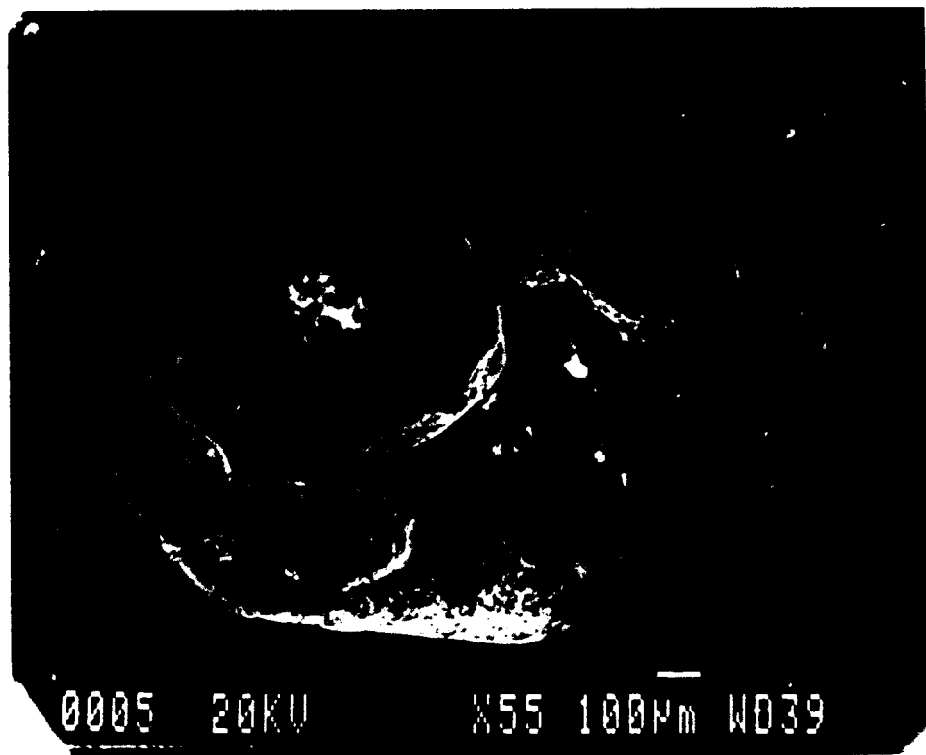


Figure 10 Intermediate Stage of the Folding of a Gold Flake in a Spherical Shape

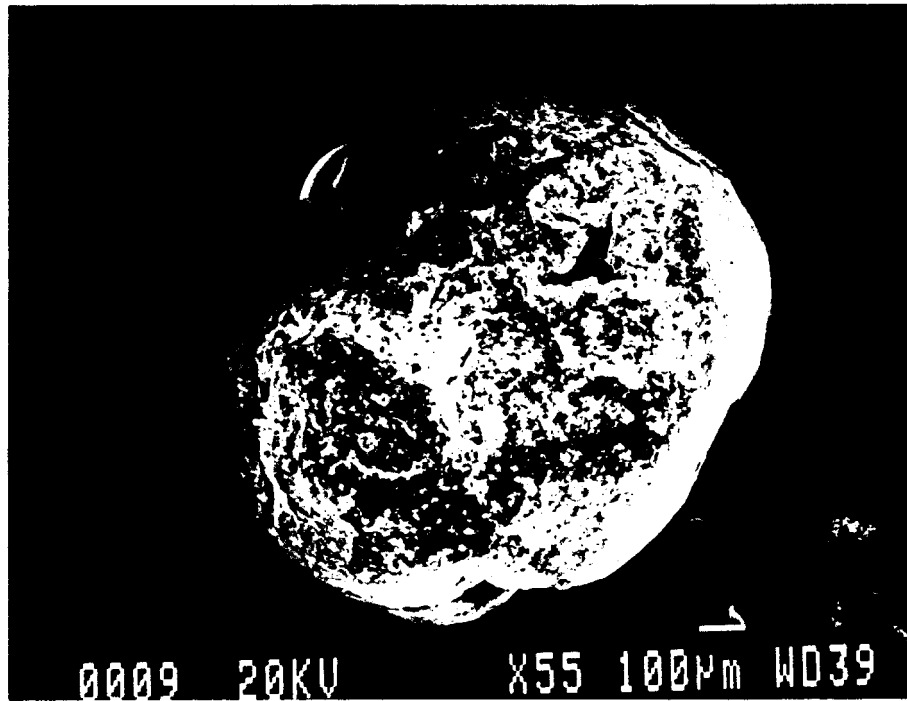


Figure 11 Final Stage of the Folding of a Gold Flake in a Spherical Shape

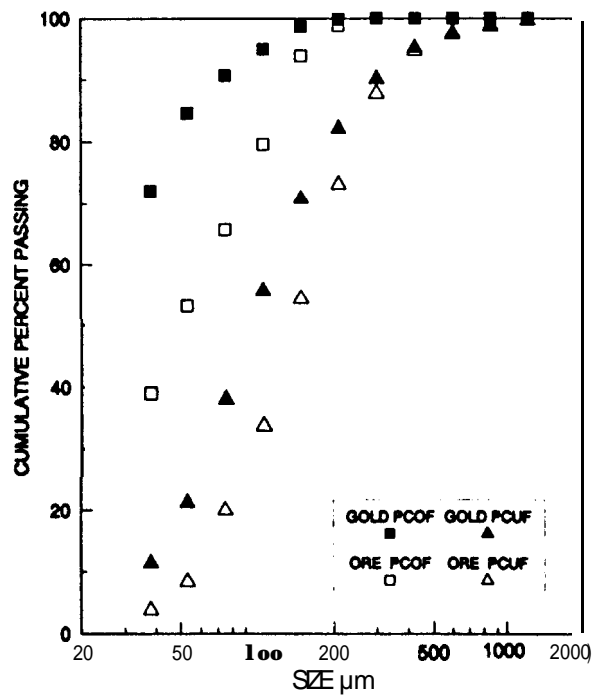


Figure 12 The Size Distribution of the Primary Cyclone Underflow and Overflow for Gold and Ore

Plant

Table 3 presents the gold content of the grinding circuit streams grades calculated from the Knelson concentrate and tails size-by-size analyses, and the corresponding Knelson recoveries.

Comparing results the duplicate tests and redundant streams is informative. First, considering the first loop, notice the close agreement between the PCUF 1 and 2 (396 vs. 400 g/t) and the SMD 1 and 2 (401 vs. 404) g/t. This shows first that the grade of both streams did not vary significantly during the test period, despite slight variations in the feed grade (PMD 1 and 2, 17.6 vs. 15.5 g/t). Agreement is also good between the PCUF and SMD, averaging 398 vs. 403 g/t. The agreement between gold recoveries achieved with the Knelson is not as good, although the PCUF and SMD all show high recoveries, between 87 and 92%. The difference in recovery for the two PMD samples is high, 27 vs. 44%; it may well stem from natural variations in the degree of gold liberation in the ore.

Table 3 Calculated Gold Content of the Grinding Circuit Streams

Stream	Gold Content (g/t)	Knelson Gold Recovery (%)
PMD1	17.6	27.1
PMD2	15.5	44.1
PCUF 1	395.6	91.2
PCUF 2	399.5	87.2
SMD1	404.3	91.3
SMD2	401.4	91.8
PCOF	15.9	39.7
SCUF1	91.0	69.1
SCUF 2	72.5	71.2
TMD	60.7	58.0
SCOF	44.5	30.7

The second circuit loop (PCOF, SCUF, SCOF, TMD) shows a different picture. First, the SCOF should assay close to the PMD and PCOF, 15 to 17 g/t; the actual grade of 44.5 g/t shows that this secondary loop had unsteady operation at the time of sampling. This is further

confirmed by the poor agreement between the SCUF 1 and 2, 91.0 vs. 72.5 g/t, and the TMD, 60.7 g/t. This may well stem from a sudden increase in the cut-size of the secondary cyclones, which releases a LARGE amount of gold to the SCOF in a short time span. As a result, the gold grade of the SCUF decreases (from 91 to 73 g/t), as the gold inventory in the secondary loop drops; this also results in a sudden increase of the gold content in the SCOF.

As a result, the focus of the study was shifted to the first loop, which produces an overflow of 66% -75 μm (200 mesh), which would be representative of the final product of a number of industrial grinding circuits (e.g. Les Mines Camchib Inc., Laplante, 1987).

Figure 12 presents ore and gold size distributions for the PCUF and PCOF. The two PCUFs are similar in size, although gold's size distribution is slightly broader (with more very coarse flakes and fines). However, gold's size distribution in the PCOF is markedly finer. To quantify how gold's breakage and classification differ markedly, its selection function and classification efficiency were estimated and compared to those of the ore.

The selection function of gold and ore in the secondary mill was calculated using a dimensionless residence time distribution, with the breakage function estimated at laboratory scale. The breakage function of the ore was assumed to be that of silica. The selection function of both species is shown in Figure 13. That of gold is significantly lower than that of the ore; the effect of particle size is different, resulting in a decreasing ratio of the two selection functions, from approximately 20 at 500-1000 μm to 6 at 50-100 μm . It can be postulated that either the aging of gold particles accelerates with decreasing particle size --i.e. the thinning and serrating of flakes requires fewer impacts for finer particles-- or that folding is less likely for finer gold particles.

Although the breakage function of gold was not estimated at plant scale, it is interesting to note that estimating the selection function with other breakage functions (measured in other systems) repeatedly yielded negative values for the selection function, as too much material was broken into finer size classes. This is an indirect validation that the breakage function values obtained at laboratory scale for gold are applicable at plant scale.

The classification function of gold is shown in Figure 14. Values below 37 μm are based on the assays of the -15, 15-25 and +25 μm , which were erratic; it appears that the weight of Knelson concentrate that was screened, 1 to 2 g, is inadequate. Future work will be performed on at least 5 g. The cut-size of the ore can be estimated at 57 μm from the classification curve; that of gold cannot be estimated with much accuracy, because of the uncertainty of the -37 μm data. However, it is clearly below 37 μm , and in the range of 15 to 20 μm . According to Plitt's model (1976), gold's D_{50} , based on that of the overall ore (density 3 g/mL), should be equal to 19 μm . The classification efficiency curve of free gold is also shown in Figure 14; it does not show much difference with that of overall gold, given a) the large fraction of free gold in the cyclone feed and b) the propensity of even gold middlings to report to the underflow.

Two features of the uncorrected recovery curve of the ore are unusual. First, the curve

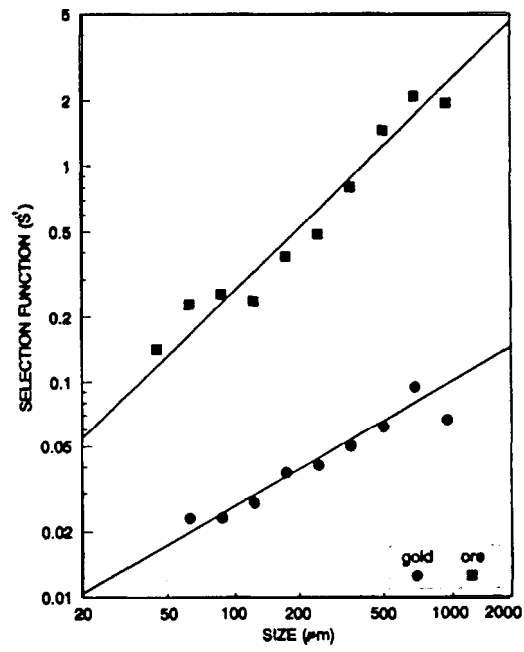


Figure 13 The Selection Function of Gold and Ore in the Secondary Mill

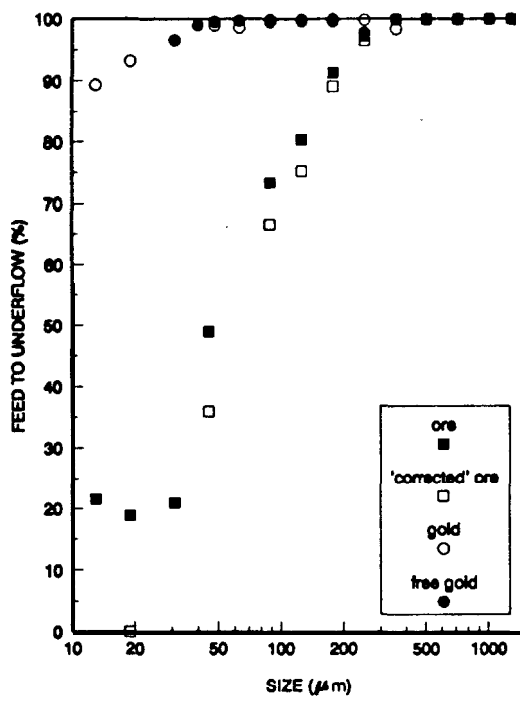


Figure 14 Classification Efficiency Curves of Gold, Free Gold, Ore, and Corrected Efficiency Curve of Ore in the Primary Cyclones

exhibits a slight hump in the 50-100 μm range; this can be attributed to the effect of sulphides, about 5 to 10% in the Hemlo ore, but probably more in the cyclone feed (as sulphides are preferentially recycled). These sulphides are concentrated in the 50-100 μm range, and their higher density results in a higher recovery to the underflow for this size range (Laplante and Finch, 1984). Second, the -37 μm section of the curve exhibits a “fishhook” effect (Finch, 1983); this has been attributed to a decrease in entrainment to the underflow with increasing particle size. The two observed features testify to the accuracy of the data, as they can easily be hidden by sampling and screening errors.

The liberation of gold can be estimated from the Knelson recovery. This method of estimating recovery is in part size dependent, and may underestimate recovery in fine streams (i.e. SCOF). Table 3 shows the recovery of various streams. Recovery is highest for the recycled streams of the first loop, PCUF and SMD. It is lowest for the PMD and the SCOF; whilst the low recovery of the PMD is indicative of lack of liberation, it is likely that that of the SCOF results from a gold size distribution detrimental to gold recovery by gravity. Further testwork is planned to determine the limitations of the 7.5 cm Knelson as a measure of free gold content.

Effect of Gold's Behaviour on its Recovery

Gold's singular behaviour has a direct impact on its recovery, whether by gravity or unit flotation within the grinding circuit, or by flotation or cyanidation in a downstream circuit.

First, when gold recovery within the grinding circuit is intended, advantage should be taken its high recycling load. This singles out cyclone under-flows and secondary mill discharges as better candidates for gold recovery. Because secondary grinding loops contain gold particles that were fine enough to be classified to the PCOF, it is unlikely that they are as good candidates for gravity recovery as recycled streams of primary loops. Not all the cyclone underflow or mill discharge need be processed. Bleeding of part the stream may well be adequate. The recovery method could be aimed at fine rather than coarse particles, as coarse particles will be recycled and can be recovered as finer fragments. The fine classification of gold also means that recycled streams should contain a significant amount of liberated gold in the range of 15 to 50 μm ; equipment that cannot recover gold in this size range is clearly suboptimal. Thus, evaluation of appropriate recovery units should be extended below 37 μm to cover the full size range of relevance.

Recovery units that are appropriate for fine gold recovery fall into two categories, centrifugal gravity and unit flotation. One possible approach could be unit flotation followed by centrifugal separation. Preconcentration could also be achieved with screening, to remove coarse particles that are unlikely to float and reduce the tonnage of ore to be treated.

When gravity recovery is not used, gold's behaviour in the grinding circuit still has incidence on its recovery downstream. First, it must be recognized that gold will be much finer than other minerals; this reduces sampling problems and improves flotation or cyanidation kinetics. Second,

gold's malleability and long residence time in the circuit is conducive to interactions with other minerals. Although embedding of harder mineral into gold particles is common and can readily be detected, the reverse phenomenon of smearing is potentially more deleterious ahead of flotation circuits, as liberated gold can become "unliberated" when smeared onto other minerals. Other potential losses of gold can occur when gold is pounded into grinding medium or liners, and these are rejected because of excessive wear. In cyanidation plants, the smearing of gold onto other minerals is not a serious problem, as smeared gold, which is obviously exposed and has a high surface area, is readily dissolved. Gold gravity recovery ahead of cyanidation would therefore not necessarily result in higher overall recovery, except when dissolved gold losses are significant, either because of an overloaded carbon circuit or the presence of preg robbers.

CONCLUSIONS

The behaviour of gold in grinding circuits is unusual; high circulating loads are the consequence of primarily grinding kinetics, and secondarily classification behaviour. Gold grinds six to twenty times slower than most other minerals, and into coarser fragments. The slower kinetics are not the consequence of hardness, but of malleability, which results in some flakes folding and assuming cylindrical and spherical shapes upon impacting. Its cut size is three times smaller than that of minerals with a density of 3 g/mL. Gold's malleability promotes interaction with other minerals and the grinding media, in the form of embedding of harder minerals into gold and smearing of gold onto other minerals. In some circuits, especially flotation, this can result in a loss of recovery, as smeared gold may be lost if the carrier particle is hydrophobic. This may lead to the decision of recovering gold with gravity or unit flotation within the grinding circuit. The recycled streams, cyclone under-flows and secondary mill discharges, are then the better candidates for recovery. High gold circulating loads make it unnecessary to process the full streams. Rather, part of the streams can be bled and presented to the gold recovery unit. Two approaches can then be taken; the first would aim for coarse gold recovery, presumably through a high capacity recovery unit such as sluices, Reichert cones, or jigs; fine gold recovery is then forfeited. The second would aim at recovering fine gold, and bleeding could be performed with a screen; coarse gold would therefore not be recovered directly, but following grinding into finer particles. The first approach appears to be the industry standard; the second, rather novel approach, offers interesting potential.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

- Austin, L.G. and Luckie, P.T., "Methods for Determination of Breakage Parameters," Powder Technology, Vol. 5, 1971/72, pp. 215-222.
- Austin, L.G. and Luckie, P.T., "The Estimation of Non-Normalizable Breakage Distribution Parameters from Batch grinding Test," Powder Technology, Vol. 5, 1971/72, pp. 267-271.
- Banisi, S., "A Methodology to Study Gold Gravity Circuits", M.Eng. Thesis, Dec. 1990, McGill University
- Epstein, B., "The Mathematical Description of Certain Breakage Mechanisms Leading to the Logarithmico-Normal Distribution," Journal of Frank. Institute, Vol. 224, 1947, pp. 471-477.
- Finch, J.A., "Modelling a Fish-hook in Hydrocyclone Selectivity Curves," Powder Technology, Vol. 36, 1983, pp. 127-129.
- Hallbauer, D.K. and Joughn, N.C., "The Size Distribution and Morphology of Gold Particles in Witwatersrand Reefs and Their Crushed Products," Journal of the South African Institute of Mining and Metallurgy, June 1973, pp. 395-402.
- Herbst, J.A. and Fuerstenau, D.W., "The Zero Order Production of Fine Sizes in Comminution and Its Implications in Simulation," Transaction of AIME, Vol. 241, 1968, pp. 538-548.
- Hodouin, D., BCrubC, M.A. and Everell, M.D., "Modelling In Industrial Grinding Circuits and Applications in Design," CIM Bull., Sept. 1978, pp. 138-145.
- Knelson, B.V., "Centrifugal Concentration and Separation of Precious Metals, 17th Annual Meeting of the CMP, Ottawa, Jan. 1985, pp. 346-357.
- Laplante, A.R. and Finch, J.A., "The Origin of Unusual Cyclone Performance Curves," International Journal of Mineral Processing, Vol. 13, 1984, pp. 1-11.
- Laplante, A.R., "Mineralogy and Metallurgical Performance of Various Gold-Copper Ores of the Chibougamau Area, Quebec," Proceedings of International Symposium on Gold Metallurgy, Eds. R.S. Salter, D.M. Wyslouzil, G.W. McDonald, Winnipeg, Aug. 1987, pp. 141-155.
- Laplante, A.R., Liu, L. and Cauchon, A., "Gold Gravity Recovery at the Mill of the Les Mines Camchib Inc., Chibougamau, Quebec," Proceedings of 22nd Annual Meeting of CMP, Ottawa, Jan. 1990, pp. 393-413

- Larsen, C.R. and R. Tessier, "Golden Giant Mine Mill Process Description and Operating Highlights", Proceedings of 18th Annual Meeting of the CMP, Ottawa, Jan. 1986, pp. 108-135
- Liu, L., "An Investigation of Gold Recovery in the Grinding and Gravity Circuit at Les Mines Camchib Inc.," M. Eng. Thesis, Dept. of Mining and Metallurgical Eng., McGill University, Sept...1990
- Plitt, L.R., "A Mathematical Model of the Hydrocyclone Classifier", CIM Bull., Vol. 69, No. 776, Dec. 1976, pp. 114-123.
- Reid, K.J., "A Solution to the Batch Grinding Equation," Chemical Engineering Science, Vol. 20, 1965, pp. 953-963.
- Spring, R., "NORBAL2," Research report N-8325; RR 85-1,1985, Centre de Recherche Noranda, Pointe-Claire, Quebec.