Iranian Journal of Science & Technology, Transaction B, Engineering, Vol. 29, No. B6
Printed in The Islamic Republic of Iran, 2005

CHARACTERIZING GRAVITY RECOVERABLE PGMS AND GOLD IN GRINDING CIRCUIT[*]

L. HUANG[1**] AND N. MEJIAB[2]

[1]Dept. of Mining, Metals and Materials Engineering, McGill University, 3610 University, Street,
Wong Building, Montreal, Qc., Canada H3A 2B2, Email: Liming.huang@McGill.ca
[2]INCO Limited, Clarabelle Mill, Copper Cliff, Ontario, Canada, P0M 1N0

Abstract– At McGill University, Canada, a successful Knelson technology for gravity recoverable gold (GRG) has been used to process more than 200 representative gold ore samples all over the world since the early 1990s. In recent years, the applications of this technology have expanded to platinum group metals (PGM). The investigation of INCO Clarabelle Mill grinding circuit products shows that, like gold, PGM selectively enrich in some of the grinding products, such as ball mill discharge and cyclone underflow, and they are amenable to gravity separation. The gravity recoverable PGMs and Au were well characterized with a combination of regular Knelson and Variable Speed Knelson technology.

Keywords – Knelson concentrator, centrifugal separation, platinum group metals, gold

1. INTRODUCTION

Since the early 1990s, the gravity research group led by Professor Andre Laplante at McGill University has been developing and optimizing a standard technology for gravity recoverable gold (GRG) with a 7.5 cm Knelson Concentrator manufactured by Knelson Gold Concentrators Inc, which is located in Langley, B.C. Canada [1, 2].

The standard laboratory procedure can simply be described as follows: a representative sample, with a size range of minus 20 mesh, is fed to a 7.5 cm diameter laboratory Knelson Concentrator. During the process several tail cuts are sampled and a concentrate is obtained at the end. The bulk tail is ground to about 50% passing 200 mesh and subjected to a second time processing with the same machine. As the first processing, tail cuts are collected and concentrate two is obtained. The second bulk tail is ground to about 80% passing 200 mesh and subjected to the third time processing. The third concentrate and tail cuts are then collected. Subsequently, all concentrates and tail samples are screened with Rotap and size-by-size assayed. The five coarse sizes of the first concentrate are subjected to a further separation with a Mini-Hydro-Separator which was developed by McGill to produce a concentrate and a tail for each size. Then, the upgraded concentrates are observed under microscope to obtain complete statistics for the coarse gold liberation. Finally, stage-by stage total GRG can be calculated and evaluated.

The great success of gravity recoverable gold technology has inspired the McGill research group to explore the possibility of using this technology in some ores other than gold. Platinum Group Metals are the first choice for this purpose, since they are precious, low in ore content and with higher specific gravity.

---

[*]Received by the editors May 8, 2005; final revised form October 19, 2005.

[**]Corresponding author

INCO Clarabelle Mill located in Sudbury, Northeastern Ontario, Canada, is one of the most famous Ni-Cu processing plants in the world, having considerable PGM contents. The throughput capacity of the mill is about 40,000 short tonnes per day. A single bulk copper-nickel concentrate is floated; a significant amount of cobalt, platinum group metal, gold and silver is also recovered during smelting. A sampling campaign of the Clarabelle Mill grinding circuit was carried out in 2002 and the samples processed in 2003.

2. KNELSON CONCENTRATOR AND ITS BASIC SEPARATION MECHANISMS

The first unit of batch Knelson Concentrator was introduced into the mineral processing industry in 1978. Nearly 3 decades of development and modification, different series Knelson Concentrators for different application purposes have been well manufactured and used in precious metals recovery industries all over the world [3-6].

The main part of the Knelson Concentrator is its truncated-cone-shape separating bowl which has several riffles where fluidization water inlets are punctured in grooves. For the regular Knelson Concentrator, the bowl rotates at a speed that produces a centrifugal force of 60 times that of gravity. The material is fed into the Knelson through a down comer. Light particles are discharged continuously through a launder as tails, while the concentrate is kept inside the grooves of the inner bowl. In industrial applications an automatic control program is designed for collecting concentrate, which includes stopping feed, flushing concentrate, and resuming feeding. For a normal 2 hour consecutive operation, it takes only a few minutes to finish the whole concentrate discharge. A 7.5 cm (diameter of the bowl) laboratory Knelson Concentrator is shown in Fig. 1 [6].

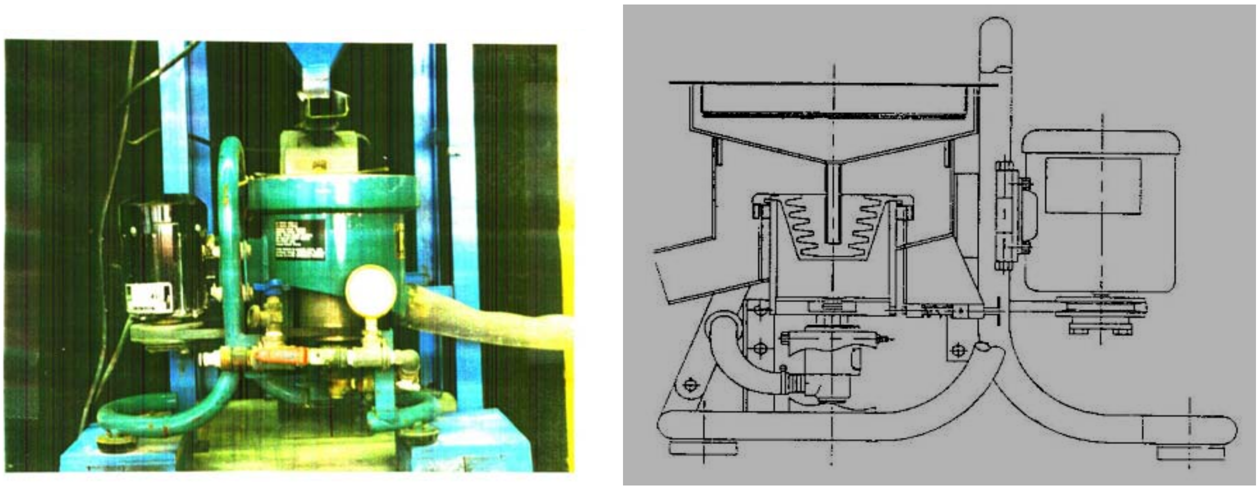

Fig. 1. 7.5 cm laboratory Knelson concentrator (left) and its schematic diagram (right)

The following is a summary of the main series of Knelson concentrators presently used in industry [5].

a) Manual discharge series (MD)

The Knelson Concentrators of this series are small ones, specially designed for the purposes of laboratory bench-scale test work, in-plant sampling, pilot scale test and in-field alluvial explorations. The dimensions of this series are 3”, 4.5” and 7.5” in diameter with a capacity of 45 kg, 275 kg and 680 kg per hour, respectively.

b) Central discharge mild steel series (CDMS)

This series was broadly used to recover gold in the early years of the Knelson Concentrator. Now more CDMS are used to process alluvial ores and for some plants which need to get a Knelson

Concentrator installed more economically. The largest one is CD30 with a capacity of 50-100 tonnes per hour, and the smallest one, CD10, has a capacity of 0.9-8 tonnes per hour.

c) Extended duty series (XD)

The XD series, with its futures of compact design, sturdy, stainless steel construction and high quality components, is for hard rock milling circuits to withstand severe operating conditions. These features of the design have made the XD series the most demanding application for precious metals recovery industry.

Centrifugal fields can be generated in two different ways. First, a fluid is introduced at a high tangential velocity into a cylinder or conical vessel such as a hydrocyclone. Generally, the larger and heavier particles will be collected near the wall of the separator, while the smaller and lighter ones will be taken off through an outlet near the axis of the vessel. The second way is the use of a centrifuge. In this case, a fluid is introduced into a rotating bowl and it is rapidly accelerated. All the fluid tends to rotate at a constant angular velocity, ω, and a forced vortex is established. The tangential velocity is directly proportional to the radius at which the fluid is rotating [7].

In most practical cases, when a particle is moving in a fluid under a centrifugal field, gravitational effects will be comparatively small, and can therefore be neglected. The equation for the particles in the centrifugal field will be similar to that for the motion in the gravitational field, except that the gravitational acceleration 'g' must be replaced by the centrifugal acceleration $r\omega^2$ [7]. The centrifugal acceleration is given by

$$a = r\,\omega^2 \tag{1}$$

For the laboratory 3” Knelson Concentrator, substituting r = 2.51 cm (the distance from the middle to the centre of the third ring), rpm = 1462, the centrifugal intensity is about 60 'g'. Assuming all particles to be spherical, the centrifugal force, the main force acting on a particle in the Knelson Concentrator, is equal to

$$F_c = \frac{\pi}{6} d^3 (\delta - \rho)\, r\,\omega^2 \tag{2}$$

where

F_c: centrifugal force acting on a particle, $g.cm.s^{-2}$
d: diameter of a particle, cm
δ: specific density of a particle, $g.cm^{-3}$
ρ: density of a medium, $g.cm^{-3}$
r: rotating radius of a particle, cm
ω: angular velocity, $radian.s^{-1}$
v_t: velocity at time t, $cm.s^{-1}$

The main forces acting on a particle inside the Knelson Concentrator are centrifugal force and axial drag force. For the drag force, it is assumed that [8, 9], under laminar flow conditions, the drag force on a spherical particle was entirely due to viscous forces within the fluid (Stock's equation), and can be described as,

$$F_d = 3\,\pi\, d\, v_r\, \mu \tag{3}$$

where

F_d: inward drag force, $g.cm.s^{-2}$
v_r: velocity at radial distance r, $cm.s^{-1}$
μ: the viscosity of the fluid medium, 0.01 $g.cm^{-1}.s^{-1}$ for water at 20 °C

If the effects of the fluidization water and other forces on the particle are not considered, the particle reaches its terminal settling velocity when F_c equals F_d. Because we mainly consider the behaviour of fine particles, Stokes equation could be used to approximate the terminal settling velocity in a centrifugal field by substituting $r\omega^2$ for 'g', as shown in Eq. (4) [7, 10].

$$V = \frac{d^2(\delta-\rho)}{18\mu} r\omega^2 \tag{4}$$

Why, in the centrifugal force field, can very fine particles be more effectively separated, compared to the gravity field? Eq. (5), answers this question, that is, as the centrifugal acceleration increases, the size of the critical particle (the finest particle that can be recovered) decreases [10].

$$d_{cr} = K\sqrt[4]{\frac{m^2c^2Hg}{\varpi^2 R}} \tag{5}$$

Where, K, m, and c are coefficients, H is the thickness of fluid film, and R is the average radius of the rotation drum. From this equation, it is also easy to understand why the Falcon Concentrator (or SuperBowl) can effectively recover even finer particles than the Knelson Concentrator does, since their centrifugal acceleration can reach 200 gs, compared to 60 gs of a regular Knelson Concentrator [9, 11].

3. PLATINUM GROUP METALS

Platinum Group Metals, Pt (platinum), Pd (palladium), Rh (rhodium), Ru (ruthenium), Ir (iridium) and osmium (Os), are located in Group VIII of Mendeleev’s Periodic Table. (Their main properties are illustrated in Table 1).

Table 1. Main properties of platinum group metals

Metal	Color	Density (g/cm^3)	Melting point (^{o}C)
Pt	Silver-White	21.45	1772
Pd	Silver-White	12.02	1554
Rh	Silver-White	12.41	1960
Ru	Silver-White	12.45	2310
Ir	White-Yellowish	22.65	2443
Os	Bluish Grey	22.61	3050
Comparing to Gold			
Au	Yellow	19.32	1065

Due to PGM properties of hardness, high density, high melting point and corrosion resistance, their applications include jewellery, catalytic converters, spark plugs, engine management systems, ABS, ceramic, industrial crucibles, capacitors, computer hard disks, aural implants, and micro-precision tools, etc.

Platinum is found as a free element, usually mixed with Au, Ni, Cu, Pd, Rh, Ru, Ir and Os. Pt is also found in minerals, the most important one is sperrylite, $PtAs_2$, with 56.56% of Pt and 43.44% of As, hardness 6-7, specific density 10.6, brittle and usually associated with chalcopyrite and pentlandite. An image from Sudbury, Canada is shown in Fig. 2.

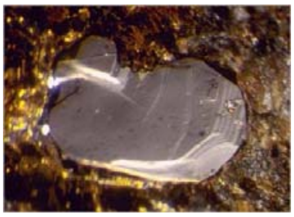

Fig. 2. The white grain of sperrylite in chalcopyrite matrix (Sudbury, Canada)

4. METHODOLOGY

a) Field sampling

November, 2002, a sampling campaign for the grinding circuit of Clarabelle Mill, INCO was carried out. Two surveys were completed, including samples of Primary Fines (as indicated in Fig. 3, the first one from right), SAG Mill Screen Undersize, #3 and #5 Ball Mill Discharge, Cyclone Underflow, Cyclone Overflow and Rod Mill Discharge, as shown in Fig. 3.

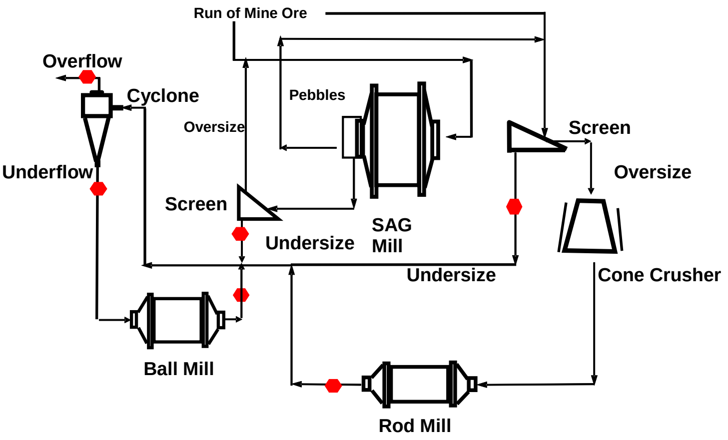

Fig. 3. Sampling diagram of Clarabelle mill grinding circuit (● sampling point)

b) Principal flowsheet of laboratory processing

Two stages of processing were carried out in a laboratory. For the first stage a 3” lab KC was used at 60 Gs, while for the second stage, a 3” Variable Speed Knelson Concentrator was used at 115 Gs to process a minus 300 µm fraction of the first stage KC tails as shown in Fig. 4.

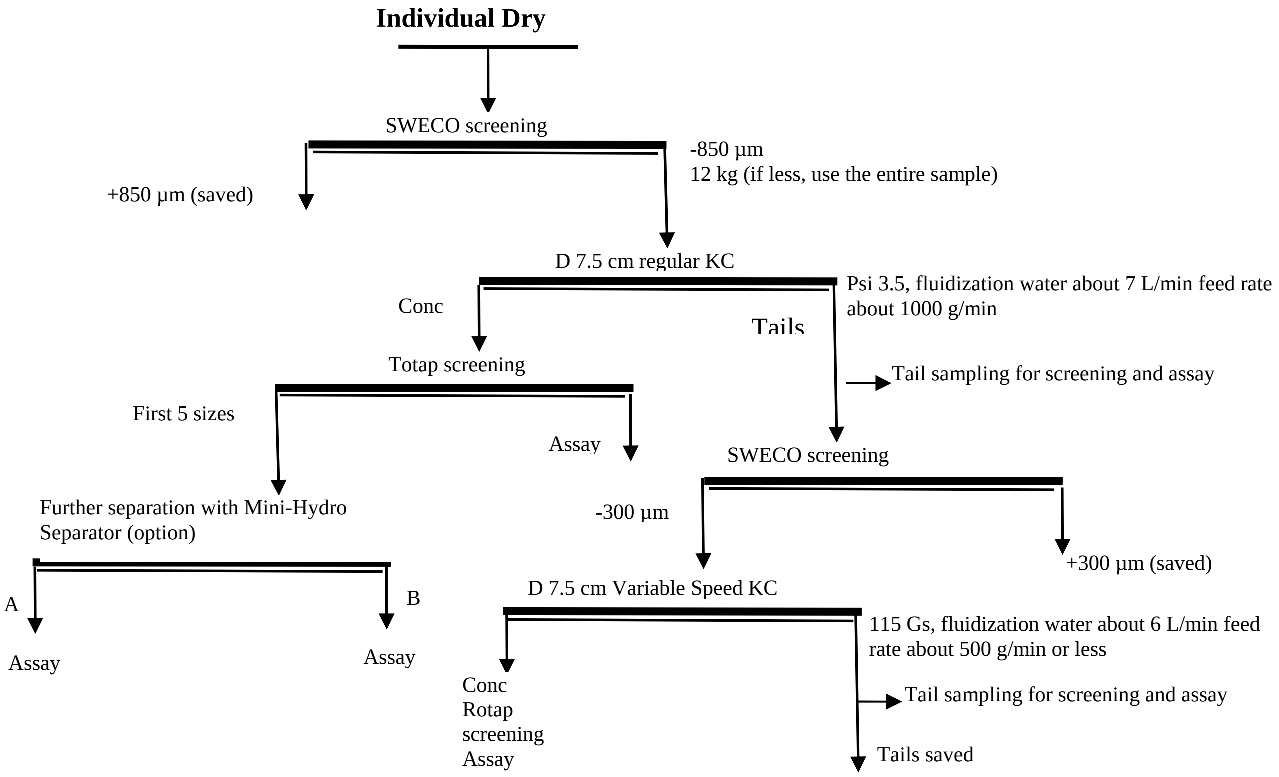

Fig. 4. The principal flowsheet of laboratory gravity processing

5. RESULTS AND DISCUSSIONS

a) The enrichment status of precious metals in the circuit

All 12 samples from the sampling campaign were tested. Concentrates and representative tail samples were sized and sent back to INCO for assaying 7 elements of Pt, Pd. Au, Ag, Rh, Ru and Ir. Results show that precious metals were selectively enriched in some streams as shown in Table 2 and Fig. 5.

Table 2. Stream grade compared to plant month main feed

	Pt	Pd	Rh	Au	Ag
Month average main (g/t), Nov. 2002	0.515	0.515	0.065	0.168	5.522
Enrichment ratio					
Ball mill discharge	5.40	3.31	1.53	19.45	2.17
Cyclone underflow	5.18	3.33	1.68	16.57	2.51
Primary fines	2.97	2.41	2.79	2.22	1.95
SAG undersize	1.35	1.49	1.05	1.61	1.25
Cyclone overflow	1.18	1.42	0.95	1.47	1.28

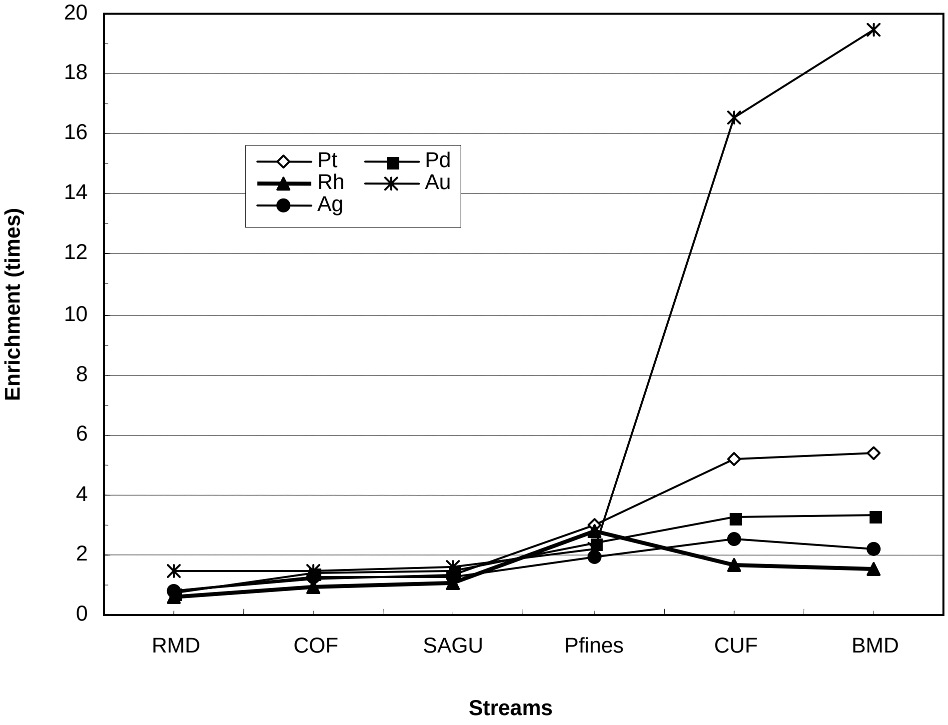

Fig. 5. Enrichment of metals in circuit streams

Table 2 and Fig. 5 show that precious metals enriched predominantly in Ball Mill Discharge and Cyclone Underflow and in Primary Fines to a certain degree, but not in other streams. According to the average grades in November 2002, the enrichments of Pt, Pd, Ag, Au Rh are 5.4, 3.31, 2.17, 19.45, and 1.53 in Ball Mill discharge; 5.52, 3.3, 2.5, 16.6, and 1.7 in Cyclone Underflow.

For gold, because of its high specific density and its great malleability and ductility, it always enriches in the grinding-classification circuit. A part of gold can accumulate there if there is no unit to recover it in time. For PGM, they also have rather higher specific densities, 21.45 for metallic Pt and 10.6 for sperrylite, which is why PGM have a similar enrichment behaviour to that of gold in grinding-classification circuit.

b) Ball mill discharge (BMD)

A summary of the results for ball mill discharge processing is given in Table 3, metals distributions in BMD are shown in Fig. 6.

Table 3. Result summery of the ball mill discharge processing

Regular 3” Knelson Concentrator							
	Pt	Pd	Rh	Ru	Ir	Au	Ag
Concentrate recovery (%)	66.74	37.67	8.00	3.94	6.64	73.89	17.69
Concentrate grade (g / t)	222.85	77.18	0.95	0.28	0.11	290.15	255.10
Feed grade (g / t)	2.777	1.704	0.099	0.058	0.014	3.267	11.993
Concentrate yield (%)	0.8320						
Enrichment	80.2	45.3	9.6	4.7	8.0	88.8	21.3
Variable Speed 3” Knelson Concentrator							
	Pt	Pd	Rh	Ru	Ir	Au	Ag
Concentrate recovery (%)	56.23	31.60	8.27	1.53	3.05	38.60	11.43
Concentrate grade (g / t)	51.46	31.09	0.48	0.05	0.07	20.08	82.74
Feed grade (g / t)	1.029	1.105	0.065	0.041	0.024	0.586	8.146
Concentrate yield (%)	1.1260						
Enrichment	49.96	28.08	7.35	1.36	2.71	34.3	10.16
Regular 3”Knelson Concentrator + Variable Speed 3” Knelson Concentrator							
	Pt	Pd	Rh	Ru	Ir	Au	Ag
Concentrate recovery (%)	84.70	56.39	15.06	5.35	9.17	80.50	25.95
Concentrate grade (g / t)	137.67	54.27	0.713	0.168	0.089	155.93	169.44
Feed grade (g / t)	2.777	1.704	0.099	0.058	0.014	3.267	11.993
Concentrate yield (%)	1.654						
Enrichment	49.6	31.9	7.2	2.9	6.4	47.7	14.1

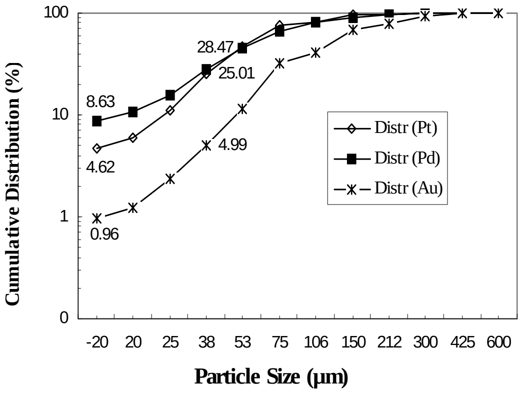

Fig. 6. Metal distributions in BMD

Size-by-size cumulative recoveries obtained by both regular Knelson and Variable Speed Knelson for Pt, Pd and Au are shown in Figs. 7-9.

Knelson concentrators can effectively recover the main components of Platinum Group Metals, Pt and Pd, with total recoveries of 84.69% and 56.37%, respectively. Gold was also well recovered at 80.50%. The results show that in the ball mill discharge, sperrylite was basically liberated. The same statues could be applicable to gold and palladium-containing mineral.

Since sperrylite is brittle, while gold is malleable, Pt and Pd were distributed more in finer sizes compared to Au. From the first stage cumulative distributions of the feed, for example, in the minus 53 µm fraction, there were 25.01%Pt, 28.47% Pd, while only 4.99% for Au (Fig.6).

A regular Knelson concentrator can effectively recover +38 µm PGM and gold. Variable Speed Knelson concentrator is a compensation for finer sizes, especially for recovering minus 38 µm PGM and gold, and even in minus 20 µm, the recoveries are still considerable.

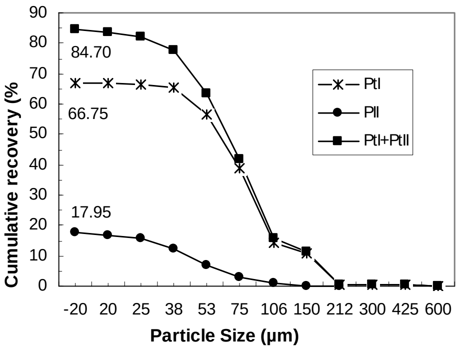

Fig. 7. Size-by-size recovery of BMD Pt

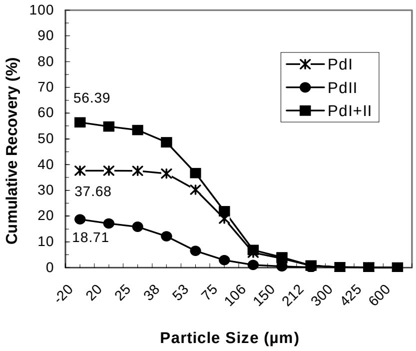

Fig. 8. Size-by-size recovery of BMD Pd

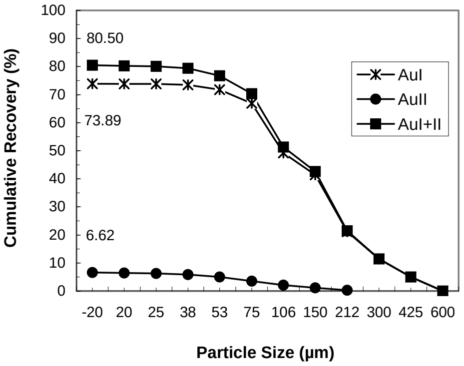

Fig. 9. Size-by-size recovery of BMD Au

In the first stage of regular KC, the highest recovery is Au, 73.89%, then Pt, 66.75%, and Pd, 37.68%. In the second stage of Variable Speed KC, Pd was the most recovered, 18.71%, then Pt, 17.95% and Au 6.62%. Why was Au recovery more than those of Pt and Pd in the first stage, while in the second stage the situation is vice versa? Besides Pt and Pd being more distributed in a finer size, it could also probably be attributed to the difference of specific density. For librated gold particles, the specific density is around 15 if it contains other alloy components such as Ag, Cu or Pt, while for sperrylite, its specific density is about 10.5. In the second stage of processing, the higher centrifugal force (115 G) of Variable Speed KC is a favourite for sperrylite fines.

c) Cyclone underflow (CUF)

A summary of the results for cyclone underflow processing is given in Table 4, metals distributions in CUF are shown in Fig. 10.

Size-by-size cumulative recoveries obtained by both regular Knelson and Variable Speed Knelson for Pt in Pd and Au in CUF are shown in Figs. 11-13.

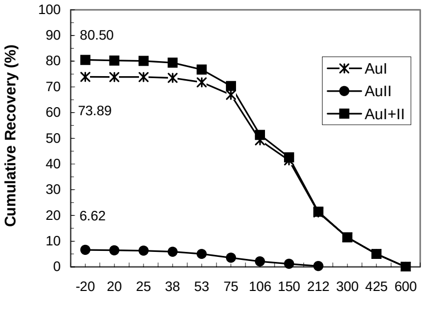

Fig. 10. Metal distributions in CUF

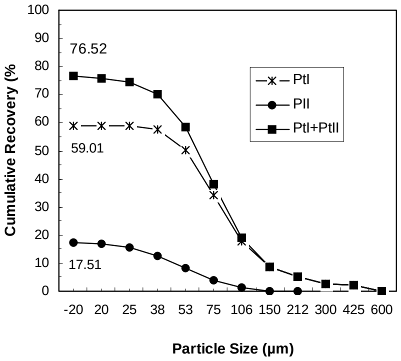

Fig. 11. Size-by-size recovery of CUF Pt

Table 4. Result summary of the cyclone underflow processing

Regular 3” Knelson Concentrator							
	Pt	Pd	Rh	Ru	Ir	Au	Ag
Concentrate recovery (%)	59.01	34.77	8.06	22.01	6.06	67.83	13.94
Concentrate grade (g / t)	186.72	70.78	1.04	0.72	0.10	225.26	229.01
Feed grade (g / t)	2.66	1.71	0.11	0.03	0.01	2.79	13.83
Concentrate yield (%)	0.8420						
Enrichment	70.10	41.31	9.57	26.15	7.20	80.58	16.56
Variable Speed 3” Knelson Concentrator							
	Pt	Pd	Rh	Ru	Ir	Au	Ag
Concentrate recovery (%)	46.47	25.97	8.27	4.68	4.10	34.36	8.65
Concentrate grade (g / t)	41.69	25.88	0.63	0.09	0.05	20.62	74.07
Feed grade (g / t)	1.23	1.37	0.10	0.03	0.02	0.82	11.75
Concentrate yield (%)	1.372						
Enrichment	33.86	18.92	6.03	3.41	2.99	25.04	6.30
Regular 3” Knelson Concentrator + Variable Speed 3” Knelson Concentrator							
	Pt	Pd	Rh	Ru	Ir	Au	Ag
Concentrate recovery (%)	76.52	49.93	14.79	25.42	9.65	77.79	19.78
Concentrate grade (g / t)	112.70	47.86	0.83	0.40	0.08	120.81	149.93
Feed grade (g / t)	2.66	1.71	0.11	0.03	0.01	2.79	13.83
Concentrate yield (%)	1.719						
Enrichment	42.3	27.9	7.6	14.5	5.7	43.2	10.8

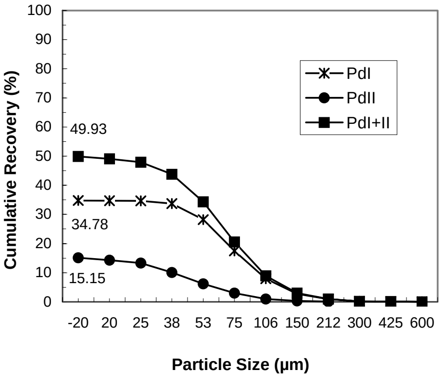

Fig. 12. Size-by-size recovery of CUF Pd

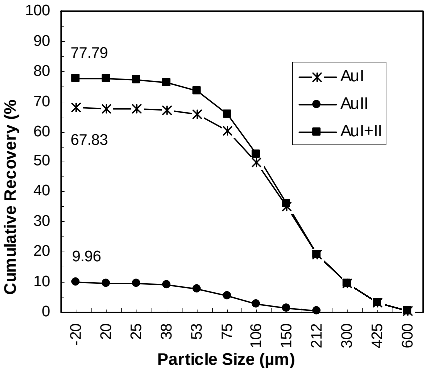

Fig. 13. Size-by-size recovery of CUF Au

The processing results of Cyclone underflow show very similar trends to those of Ball Mill discharge. Again, Pt and Pd were distributed more in finer size than Au. The distributions of Pt, Pd and Au of cyclone underflow in minus 20 µm are lower than those of Ball Mill discharge, 3.83% to 8.63% for Pd, 2.08% to 4.62% for Pt and 0.61% to 0.96 for Au, respectively, since a part of fines were classified to cyclone overflow. Good recoveries were achieved, too, 76.52% for Pt, 49.93% for Pd and 77.79% for Au, respectively.

The combination technology of regular Knelson and Variable Speed Knelson can also effectively process other products of the grinding circuit, such as Primary Fines and SAG Mill, even though there was no obvious enrichment. Those results are not shown in this paper because of the page limitation.

6. CONCLUSIONS

In the Clarabelle Mill, the main PGM-containing mineral is sperrylite which has a specific density of 10.6 and its brittle property causes more fines during grinding compared to gold.

In the grinding circuit, PGM and Au are well enriched in ball mill discharge and cyclone underflow, they have also enriched primary fines to a certain degree. For SAG Mill Undersize, Cyclone Overflow and Rod Mill discharge, the grades are basically close to the level of the plant main feed.

The combination of regular Knelson (60 Gs) and Variable Speed Knelson (115 Gs) is an effective technology to recover PGMs from both Ball Mill discharge and cyclone Underflow, and the technology is very positive for gold, too.

For the Ball Mill discharge, a total Pt recovery of 84.70% with a concentrate grade of 137.67 g/t was achieved from a feed grade of 2.777 g/t Pt, with an enrichment 49.6; a Pd recovery of 56.39% with a concentrate grade of 54.27 g/t Pd was obtained from a feed grade of 1.704 g/t Pd, with an enrichment 31.9; a Au recovery of 80.50% with a concentrate grade of 155.93 g/t was achieved from a feed grade of 3.267 g/t Au, with an enrichment 47.7.

For the Cyclone underflow, a total Pt recovery of 76.52% with a concentrate grade of 112.70 g/t was achieved from a feed grade of 2.66 g/t Pt, with an enrichment 42.3; a Pd recovery of 49.93% with a concentrate grade of 47.86 g/t Pd was obtained from a feed grade of 1.71 g/t Pd, with an enrichment 27.9; a gold recovery of 77.79% with a concentrate grade of 120.81 g/t was achieved from a feed grade of 2.79 g/t Au, with an enrichment of 43.2.

Acknowledgements- With special thanks to the Manager of Clarabelle Mill, Mrs. Daryl McNamara, and the Superintendent of Process Technology Mr. Andy Kerr.

Surveys of grinding circuits were well organized and carried out with the great help of the Clarabelle Mill Laboratory, hearty thanks to Process Engineer, Mr. Noël Mejia, Plant Technologist, Mr. Yvon Shields and Engineer (in training) Bethan McKevitt.

Many thanks to McGill University Professor Andre Laplante who organized and supervised the sampling and laboratory tests; special thanks to Mineral Processing Laboratory technician of McGill University, Ray Langlois, and McGill graduate student Mr. Tapiwa Chenje for their great help during sampling campaign.

REFERENCES

1. Laplante, A. R., Woodcock, F. & Noaparast, M. (1994). Predicting gold recovery by gravity, *Proceedings Annual Meeting of SME,* Albuquerque, Paper 94-158.
2. Woodcock, F. & Laplante, A.R. (1993). A laboratory method to measure free gold content, *Proceedings of Randol Gold Seminar,* Beaver Creak, September. 151-155.
3. Knelson, B. V. (1988). Centrifugal concentration and separation of precious metals, *2nd International Conference on Gold Mining*, Vancouver, Nov. 303-317.
4. Knelson, B. V. (1990). Development and economic application of Knelson concentrator in low grade alluvial gold deposits, *The AusIMIM Annual Conference*, Rotorua, New Zeeland, March 18-21, 123-128.
5. Knelson, (2004). *Batch Knelson Concentrator*. (booklet), 6 p.
6. Huang, L. (1996). Upgrading of Gold Gravity Concentrates. A Study of the Knelson Concentrator, Ph.D. Thesis, 294 p.
7. Coulson, J. M., Richardson, J. F., Backhurst, J. R. & Harker, J. H. (1991). *Chemical Engineering*, *2*, Fourth Edition, Particle Technology and Separation Processes, Pergamon Press, Oxford, New York, 1991, 968p.
8. Stokes, G. G. (1901). Mathematical and Physical Papers, *Trans. Cambridge Phil. Soc., 9*, Part II, 51ff.
9. Sutter, J. (1997). Super Bowl nominal specifications, http:/www.rmsross.com/sb_spec.htm, April 30.
10. Sun, Y. (1982). *Gravity Separation*, Metallurgy Press, Beijing, 310 p. (Chinese Text).
11. McAlister, S., (1992). Case study in the use of the Falcon gravity concentrator, *Proceedings of 24th Annual Meeting of the Canadian Mineral Processors*, Ottawa January, 20 pages.