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Application of radiotracers as tools to determine feed flowrate imbalances and particle size segregation in industrial flotation circuits

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Abstract: This publication presents the application of radiotracers in the characterization of industrial flotation circuits. Two examples are showcased: the detection of feed flow rate imbalances and the characterization of particle size segregation in automatic mineral-cutting machines. The feed pulp distribution was determined from the mean residence times. Particle size segregation was measured by sampling the cutting machines (≅ 25 grams samples) using coarse, intermediate, and fine-sized radiotracer particles. Radiotracers were injected into the feed streams and measured at various points of the circuit using nuclear instruments, allowing for non-invasive and real time detection. Results show that in the rougher flotation stage, the feed flow is distributed almost evenly in lines 2 and 3 (approximately 38% of the flow goes to each line) and to a lesser extent towards line 4 (approximately 24%). In lines 1 and 2 of the scavenger stage, a higher percentage of the flow goes towards line 1 (approximately 59%) and a lower percentage towards line 2 (41%). Line 6 of the rougher flotation is the fastest of the circuit (shortest residence time). In addition, the inlet mineral-cutting machine of the rougher stage segregates particles with a bias for fine sizes (11.4 % more fine-sized particles than coarse ones). This work is an example of how radiotracer technology can be applied to improve metal production and processes. Radiotracers provide reliable information to be used in combination with other metallurgical data to properly assess flotation circuits.

Keywords: radiotracers, flotation, particle size segregation, feed flow distribution

1. Introduction

A typical problem found in flotation circuits is the unknown feed flow distribution in parallel banks. The feed flowrate distribution is not usually measured in real time and imbalances have been reported in industrial operations (Henríquez et al., 2022; Yianatos et al., 2012; Yianatos and Diaz, 2011). An even flow distribution is generally assumed for mass balance purposes, but this assumption is in practice unrealistic. The guess clearly biases metallurgical characterization and hinders the determination of performance indicators. Moreover, the costs of an incorrect assumption are high: an uneven feed flow distribution causes detrimental effects such as segregation of solids, changes in metal grades, and instability of control systems.

The solution to unknown flow distribution is of course characterizing the circuit and determining the real flow rate value for each row after the feed distributors. A suitable tool for this is the use radioactive tracers. Radiotracers are generally used to diagnose causes of inefficiency in plants and those environments where a great cost-benefit ratio can be gleaned from process optimization (IAEA, 2004). Radioactive tracers have been previously used to characterize flotation processes (Vinnett et al., 2023; Gaudin et al 1948), specifically to track the path of the difference phases (e.g., solid, liquid) in the circuit (Yianatos et al., 2015; Bogdanov et al., 1957). Radiotracers can be measured online (sampling rates of the order of 1 second) and non-invasively. Gamma radiotracers are of particular interest since the measurement of gamma radiation can be made through steel and cement walls. These characteristics make gamma radioactive tracers ideal for its use in industrial environments.

Another difficulty frequently encountered is the discrepancy between particle size data obtained by sampling mineral-cutting machines and benchmark data provided by discrete sampling methods (e.g.,

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gravimetric analysis). This can happen because cutting machines segregate particles with a bias for a specific size and favour its presence. Characterizing particle size segregation sheds light on this matter (especially in the feed towards the flotation cells). Indeed, ore grain size changes during circuit operation and as a result the recovery of valuable metals (Arellano et al., 2023). The metal concentration in each stream is linked to the mineral particle size (Beamer et al 2012), with a higher concentration observed with smaller particles. Gamma radiation tracers can be used to trace mineral particles of different sizes and measure the change in ratio between the masses of the coarse and fine fractions. This facilitates the determination of particle size segregation and the bias of mineral-cutting machines.

This work presents the application of radiotracers as diagnostic tools to assess a flotation circuit. Valuable insights into process dinamycs and material flow patterns are provided. The information obtained is useful for control processes and metallurgical optimization strategies, allowing for a more efficient and cost-effective flotation process. The objective of this paper is to characterize feed flow distributions in rougher and scavenger flotaton stages. Residence time values were used to characterize the circuit kinetics, including determining the fastest and slowest lines. Mineral particle size segregation for each stream and the bias of the mineral-cutting machines were also determined.

2. Materials and methods

2.1. Rougher and Scavenger flotation circuits

Fig. 1 and Fig. 2 show the rougher and scavenger flotation circuits, respectively. The rougher circuit processes a copper ore with grades around 0.7%. It consists of eight parallel flotation banks and three main SAG (semi-autogenous) grinding lines. Lines 1 to 4 consist of Dorr-Oliver Eimco cells (250 m^3). Lines 5 to 8 consist of Wemco Cells (130 m^3). The scavenger stage consists of two lines and 18 Wemco cells (130 m^3).

Liquid and solid tracers were injected into the feed distributor tanks before the feeding lines. Fig. 3 shows the flow distribution in the rougher stage. A is the distributor that feeds rougher lines 6, 7 and 8. B is the distributor that feeds rougher lines 1, 5 and 6. Volumetric pulp flow rates were calculated using effective volumes and mean residence times (Levenspiel, 1998).

Gamma radiation detectors were located at the input and output streams of specifically selected flotation cells. Circuit throughput was 6500 tph.

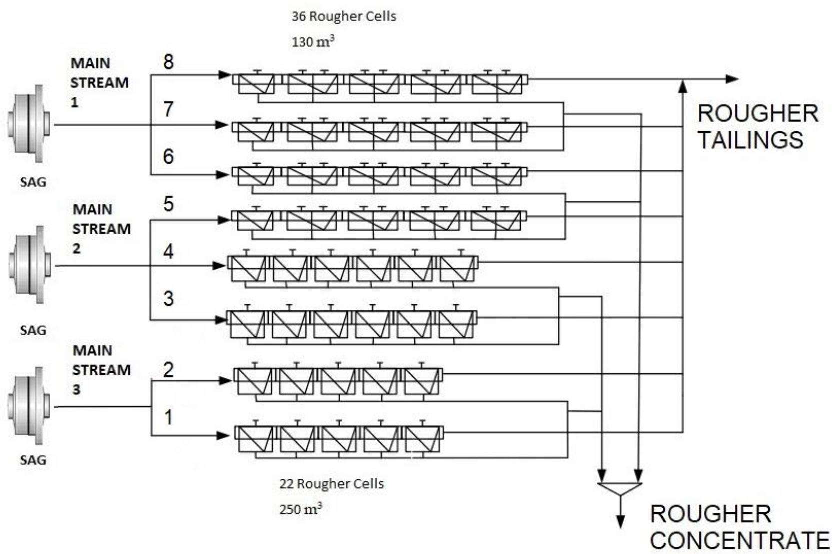

Fig. 1. Rougher flotation circuit. The three main streams are fed by semi-autogenous grinding (SAG) mills

2.2. Radioactive tracer technique

To trace the liquid phase, a tiny amount of radioactive liquid (Br^{82} in solution) was injected into the flow. The injection was achieved as a pulse. Br^{82} was chosen as radiotracer due to its chemical and physical properties, which make it an excellent tracer for liquids (IAEA 1983; ISO 2975-7:1977).

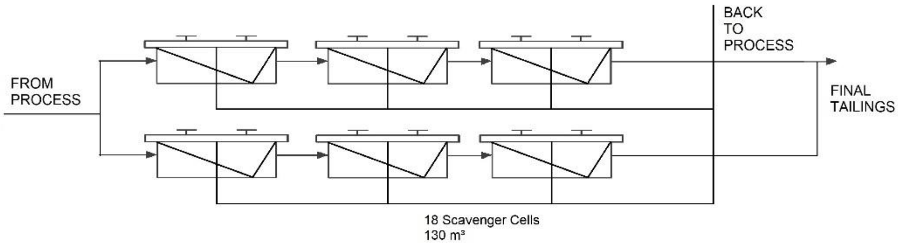

Fig. 2. Scavenger flotation circuit

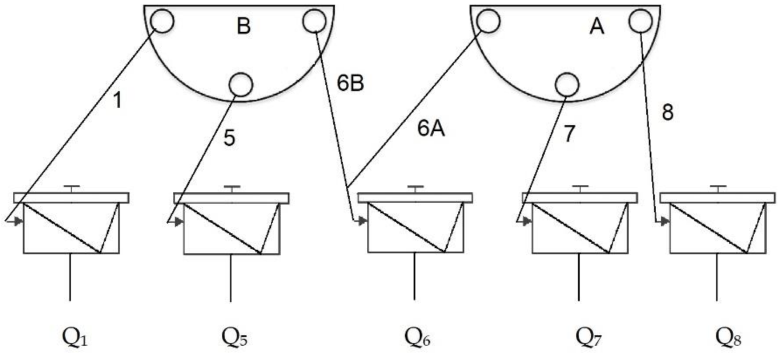

Fig. 3. Flow distribution in the rougher flotation. Distributors A and B are used to feed lines 1, 5, 6, 7 and 8 of the rougher stage

Irradiated non-floatable solids were used to trace the solids. Solids were sampled from the plant tailings and classified and tested in three classes: coarse+150; medium: -150+45, fine-45 microns. These three classes were chosen to: a) consider the effect of solid segregation in flow distribution b) assess the performance of the pulp-cutting machines.

Samples were irradiated at the nuclear reactor of the Chilean Commission of Nuclear Energy (5 thermal MW reactor using a neutronic flux of up to 5×10^{13} n/cm^2 s., spatially homogeneous in 4π). The tracer lifetimes were 15 h and 36 h for the solid and liquid, respectively. The selected activated element in the solid samples was Na^{24}. Br^{82} was obtained from irradiated KBr. Amounts between 30 and 50 mCi of Na^{24} were calculated to provide enough significance (50 times) above on-site radiation backgrounds.

Radiation measurements were performed online using 1 "x1.5" NaI (Tl) scintillation detectors (Saphymo, Montigny-le-Bretonneux, France). Detector probes were connected to data acquisition systems. This allowed the simultaneous acquisition of data from up to 12 control points, with minimum intervals of up to 10 milliseconds. Detectors were collimated to monitor tracer radiation with negligible interferences from other sources.

2.3. Measurement of mean residence times

Radiation measurement data was corrected by radioactive decay and background radiation (IAEA 2004). This is shown in Equation (1):

$$I_{net}(t) = (I_{measured} - BG) \cdot e^{\frac{0.693 \cdot t}{t_{1/2}}} \tag{1}$$

where I_{net} is the net radiation intensity (corrected by background and radioactive decay). $I_{measured}$ is the radiation from the samples. BG is the background radiation; t is the measurement time; $t_{1/2}$is the half-time of the tracers.

Residence times were calculated using the method of moments (IAEA 2001) as shown in Equation (2):

$$t_{exp} = \frac{\int_0^\infty t\, C(t)dt}{\int_0^\infty C(t)dt} \tag{2}$$

where t_{exp}: mean residence time, t: measurement time, $C(t)$: tracer concentration over time. Tracer data was normalized by the concentration at the outlet C_0.

2.4. Characterization of mineral-cutting machines

Mineral-cutting machines were used to reduce particle size before flotation cells. They were located at the inlet and outlet of the rougher stage, and at the outlet of scavenger circuit (return line). Radiotracers were used to identify if machines were cutting mineral particles with a bias for a specific particle size. This bias was quantified by measuring the change in ratio between the radiation from the masses of the coarse and fine (or intermediate) fractions at two different points (inlet and outlet of the circuit in Fig. 4). Solid radiotracers of three size classes (see 2.2) were injected at the inlet and collected at the outlet of each machine (Fig. 4). A 0.25 m^3 mixer vessel was used to ensure well-mixed conditions for sampling. 1000 cm^3 (0.001 m^3) samples were collected and located at the centre of a second vessel (0.2 m^3) containing a gamma radiation detector. Water was used as a radiation shield, minimizing background radiation, and ensuring that the detector received radiation coming only from the sample. A single time sample was taken.

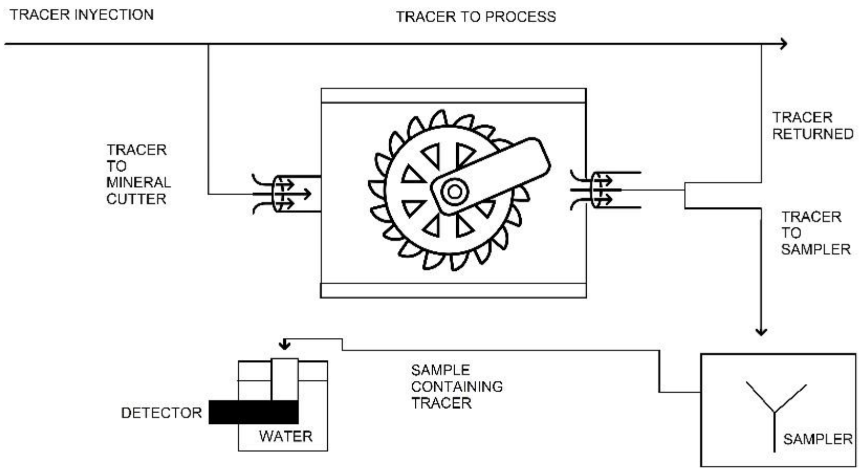

Fig. 4. Evaluation of mineral-cutting machine performance. Machines were located at the inlet of the rougher and scavenger flotation circuits. A well-mixed container (sampler) and a vessel containing a gamma detector were used

Values of net radiation intensity I_{net} were corrected by an activity factor F_a and a flow factor F_f. The purpose of these factors was to consider field conditions. This is shown in Equation (3):

$$I_C = I_{net} \cdot F_a \cdot F_f \tag{3}$$

where I_C is the corrected intensity.

The bias of the cutting machines was determined using the intensity difference between I_{net} (coarse particles) and I_C. This was calculated from Equation (4).

$$ID = \frac{I_{net} - I_C}{I_{net}} \cdot 100 \tag{4}$$

where ID (%) is the intensity difference between particle sizes. This value is the machine bias.

3. Results and discussion

3.1. Detection of feed flow rate imbalances

Lines 1, 5, 6, 7 and 8 of the rougher flotation were examined first. Fig. 5 exemplifies the radiotracer measurements in the inlet and outlet streams of cells 1, 3 and 5 of the sixth line, using solid tracers (fine sizes). This data was used to calculate the mean residence times according to Equation (2).

Table 1 summarizes the mean residence times values for each line, classified per solid size. Solid segregation is observed. Significant differences in mean residence values indicate an uneven flow distribution. It is noted that line 6 is the fastest of the circuit (lower residence times).

In addition, residence times for intermediate sizes are comparatively higher in all lines. A decreasing trend towards coarse particle sizes is observed (consistently the lowest residence times). This agrees with previous studies (Yianatos and Diaz, 2011).

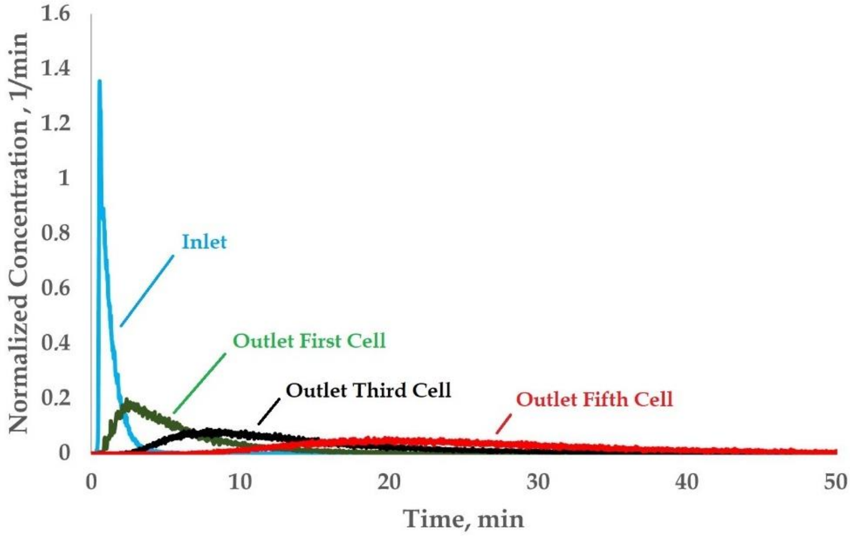

Fig. 5. Normalized tracer concentration in the inlet and outlet of the first, third and fifth cells of the sixth line of the rougher stage. Fine solid tracer

Table 1. Mean residence time for rougher lines 1, 5, 6, 7, and 8

Size	t1 [min]	t5 [min]	t6 [min]	t7 [min]	t8 [min]
Fines	4.7	5.6	4.6	7.3	9.5
Intermediate	5.4	5.8	4.6	7.7	9.6
Coarse	4.3	4.7	3.8	6.8	8.1

Table 2 shows the estimated mineral pulp distributions among lines 1, 5, 6, 7 and 8. Percentage distribution was estimated from the mass balance equations describing Fig. 3. This is Equation (5), Equation (6) and Equation (7):

$$Q_a + Q_b = Q_1 + Q_5 + Q_6 + Q_8 \tag{5}$$

$$Q_6 = Q_{6A} + Q_{6B} \tag{6}$$

$$Q = \frac{V_{eff}}{t_{exp}} \tag{7}$$

where Q is the volumetric pulp flowrate for each stream. V_{eff} is the effective volume of the cells and t_{exp} the mean residence time. V_{eff} considers the gas hold-up in the flotation machines.

Data in Table 2 confirms that line 6 is the fastest of the circuit, as it consistently presents higher flow rates and percentages of flow distribution. This is consistent with Fig. 3 which shows that line 6 collects flow from two distributors (A and B). Line 6 receives more flow from distributor A compared to distributor B. The exact proportion is 70% and 30%, respectively.

Lines 2, 3 and 4 of the rougher flotation were examined in a second survey. Residence time calculations were performed as previously described for the other lines. Table 3 shows the flow distribution results. Values indicate a clear flow imbalance with line 4 showing consistently the lowest flow rates. Lines 2 and 3, however, are distributed almost evenly.

Table 4 shows the flow distribution results for the scavenger stage. Only fine sizes were analysed. A higher percentage of the flow goes towards line 1 (approximately 59%) and a lesser percentage towards line 2 (41%). As reported previously (Henríquez et al., 2022) significant flow rate imbalances negatively affect the metallurgical performance and hinder circuit operation. Therefore, recommendations were made to plant operators for changing the valve setting of the feed distributor to improve pulp distribution.

Results show the importance of robust and reliable flowrate detectors to detect imbalances at industrial scale. Radiotracers are suitable tools for this purpose.

Table 2. Flow Distribution and mean percentages in rougher lines 1, 5, 6, 7, and 8

Test	**Line 1**		**Line 5**		**Line 6**		**Line 7**		**Line 8**	
	Q_1 [m³/h]	**Q_1 %**	**Q_5 [m³/h]**	**Q_5 %**	**Q_6 [m³/h]**	**Q_6 %**	**Q_7 [m³/h]**	**Q_7 %**	**Q_8 [m³/h]**	**Q_8 %**
Fine Solids	2185.5	25.0	1827.8	20.9	2257.6	25.8	1407.1	16.1	1079.0	12.2
Intermediate Solids	1906.7	22.9	1771.7	21.3	2247.2	27.0	1335.7	16.0	1074.2	12.8
Coarse Solids	2265.3	23.8	2049.3	21.5	2576.0	27.1	1426.7	15.0	1195.7	12.6
Mean	2119.2	23.9	1882.9	21.2	2360.2	26.6	1389.8	15.7	1116.3	12.6

Table 3. Mean flow distributions for solid tracers in the rougher stage. Lines 2, 3 and 4

Tracer	Line	Mean (%)
Fine solids	2	35.3
	3	38.7
	4	26.0
Intermediate solids	2	36.6
	3	38.8
	4	24.6
Coarse solids	2	39.7
	3	37.7
	4	22.6

Table 4. Mean flow distributions for solid tracers in the scavenger stage

Tracer	Line	Mean (%)
Fine solids	1	58.8
	2	41.3

3.2. Characterization of the bias of mineral-cutting machines

The three particle sizes entering the mineral-cutting machines of the rougher stage were evaluated. Values of measured and net radiation intensity for coarse, fine, and intermediate particle sizes are shown in Table 5 and Table 6. Table 5 shows values for the inlet cutting machine and Table 6 for the outlet cutting machine.

Table 5. Input parameters for I_{net} calculation. Evaluation of the mineral-cutting machine at the inlet of the rougher flotation

Input parameter [unit]	Coarse	Fine
$I_{measured}$ [cps]	360.3	617.5
BG [cps]	105.6	102.8
I_{net} [cps]	254.7	514.7

After I_{net} calculation, the intensity difference (ID%) was calculated as described in Equation 4. For fine particles, values in Table 7 (first row) show that the inlet cutting machine segregates particles with a bias for fine sizes (11.4% more fine-sized than coarse ones). Rows 2 and 3 show the bias values for the outlet machine. The bias for fine sizes is the highest (60% more fine-sized particles than coarse ones) and the one for intermediate sizes is important (12.2 % more intermediate particles than coarse ones). Bias in measurement for these machines may cause an overestimation in copper recovery (due to higher concentrations present in fine-sized particles).

The outlet machine of the scavenger stage was also investigated. Only coarse and fine particles were measured at this stage. Table 8 shows the input parameters for I_{net} calculation. Table 9 shows that the cutting machine has a bias for fine sizes (4.6% more fine-sized particles than coarse ones). Bias is lower compared to the rougher stage. This was attributed to the milder operational conditions (smaller particle loads and less stress).

It should be noted that bias values are highly dependent on the flowrate (characterized by the flow factor) and the plant operation conditions. Operational conditions were stable during experiments with cutting machines.

To avoid particle segregation the following measures were recommended to plant operators: a) visually inspecting inside the cutting machines looking for defects, b) improving mixing by increasing turbulence before cutting machines.

Table 6. Input parameters for I_{net} calculation. Evaluation of the mineral-cutting machine at the outlet of the rougher flotation

Input parameter [unit]	Coarse	Fine	Intermediate
$I_{measured}$ [cps]	421.1	530.2	452.1
BG [cps]	166.6	166.6	166.6
I_{net} [cps]	254.5	363.3	285.5

Table 7. Evaluation of the mineral-cutting machines of the rougher flotation. I_{net} from coarse particles was used as a reference when calculating ID (%)

Location	$I_{net\text{-}coarse}$ [cps]	Fa	Ff	I_C [cps]	ID (%)
Inlet machine (fine to coarse particles)	254.7	1.04	0.53	283.7	-11.4
Outlet machine (intermediate to coarse particles)	254.5	1.00	1.00	285.5	-12.2
Outlet machine (fine to coarse particles)	254.5	1.12	1.00	407.2	-60.0

Table 8. Input parameters for I_{net} calculation. Evaluation of the mineral-cutting machine at the outlet of the scavenger flotation

Input parameter [unit]	Coarse	Fine
$I_{measured}$ [cps]	469.9	805.1
I_{net} [cps]	313.3	642.7
BG [cps]	156.6	162.4

Table 9. Evaluation of the mineral-cutting machine at the outlet of the scavenger flotation. I_{net} from coarse particles was used as a reference when calculating ID (%)

Location	I_{net} [cps]	Fa	Ff	I_C [cps]	ID (%)
Outlet machine (fine to coarse particles)	313.3	0.51	1.0	327.8	-4.6

4. Conclusions

Radiotracer tests were carried out in both rougher and scavenger flotation circuits. The mineral-cutting machines were also studied. The following conclusions are highlighted:

- Line 6 is the fastest of the rougher flotation. This was expected since line 6 collects flow from two distributors (A and B). However, data should be compared to design values. Flotation lines with a residence time shorter than design are more sensitive to mineral losses.
- Data shows that mineral cutting machines are capable of processing pulps containing the three particle sizes studied. There is no particle size (including fine and coarse particles) that is not processed. The inlet cutter of the rougher flotation takes 11.4% more fine particles than coarse ones.

The radioactive tracer technique has proven to be a suitable methodology to estimate the mean residence times of liquids and solids in flotation circuits. The method allowed to identify unbalanced flow rate conditions between parallel rows as well as to suggest circuit improvements. Particle size segregation was also determined, and the bias of the mineral-cutting machines characterized. Further studies are being conducted on the development of empirical correlations relating particle size distribution to parameters such as copper concentration in the streams.

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