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Optimizing industrial flow measurements in mineral processing: Utilizing radiotracers for enhanced data reliability within Mining 4.0.

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Abstract: As the mining sector undergoes rapid transformation, Industry 4.0 principles — such as data digitalization, process automation, and Big Data Analytics — are crucial for developing intelligent mineral processing plants. These principles advance processes towards an interconnected sequence of steps, each relying on high-quality data. Within this framework, low-uncertainty flowmeter data is vital for accurate metallurgical mass balance determination, efficient process control, and the correct application of advanced analytical tools. However, harsh mining conditions can cause significant deviations in flowmeter readings, necessitating robust data validation methods. This paper introduces the novel application of the radiotracer methodology, which provides certified uncertainties around 1%, to optimize flowmeter data accuracy and align with Mining 4.0 requirements. Three industrial validation examples are presented: Flow meter adjustment in leaching processes, evaluating a NaHS loop piping circuit in a molybdenum flotation plant and validating flow meters to assess the hydraulic behavior of recirculation pumping stations for water balance quantification. On-site validations at the leaching plant revealed that only 36% of the measurements were within the acceptable 5% error margin. Flow assurance was confirmed in the NaHS loop piping circuit as radiotracer velocity data showed no blockages. Deviations in the recirculation pumping stations, ranging from 6.91% to 22.55%, highlighted the need for flowmeter adjustments. These findings underscore the value of radiotracers as a validation method. This paper also provides insights for water and environmental impact assessment, metallurgical mass balance calculations, and process optimization, emphasizing the need to integrate radiotracer methodology within the Mining 4.0 framework.

Keywords: flowmeter data, Mining 4.0, radiotracers, measurement uncertainty, process optimization

1. Introduction

In today's era of Industry 4.0, data can be regarded as the critical fuel that drives trusted analytics and insights. While data holds immense value, its utility is significantly diminished if it remains fluctuant and untrustworthy. Ensuring data reliability is a fundamental objective of modern precision metrology and data integrity initiatives across diverse industries (Schuh et al., 2013; Kehinde et al., 2024). Accurate and reliable data empowers business leaders to eliminate guesswork and make well-informed decisions, especially in process-driven industries such as mineral processing. In such industries, the interconnected nature of production systems amplifies the impact of inaccurate or inconsistent data, as errors can propagate through multiple operational stages, affecting efficiency, sustainability, and compliance with regulations (Bousdekis et al., 2021).

Process data generated by analog meters inherently involves measurement uncertainty, which necessitates defining acceptable uncertainty ranges to ensure data reliability. To maximize utility, measurement values should be traceable to international standards, with uncertainty minimized to meet practical and operational needs. In process industries, achieving a 95% accuracy level is common practice, but higher levels of precision are often desirable, particularly in critical operations. Among flow rate measurement techniques, the radiotracer transit time method stands out as the most precise standard for on-site validation. This technique provides traceable references for turbulent flows of both pure liquids and pulps, achieving certified uncertainties below 1% (ISO 2975-7:1977; Kuoppamaki, 2006;

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Gonçalves et al., 2021). Such precision is essential for enhancing flowmeter data accuracy in alignment with the demands of Industry 4.0.

Beyond flow validation, radiotracers are instrumental in characterizing complex mineral processing unit operations, including flotation, leaching, and milling (Vinnett et al., 2022; Diaz and Barrientos, 2024; Vinnett et al., 2024). This versatility extends to applications where radiotracer data can complement emerging technologies, such as machine learning, to enhance process monitoring and predictive modeling. Recent studies, such as El-Tokhy et al. (2025), demonstrate the integration of residence time distribution analysis from radiotracer signals with machine learning techniques to diagnose malfunctions in industrial processes. Comparative data analysis using radiotracer insights provides valuable input for improving metallurgical balance calculations and optimizing plant performance (Barrientos et al., 2022; Diaz and Barrientos, 2023). As digitalization and automation continue to advance, the integration of radiotracers with data-driven technologies represents a powerful tool for addressing modern industrial challenges.

In mining, the growing scarcity of water has emphasized the critical need for accurate water flow measurements. Water is indispensable for mineral processing operations such as grinding, flotation, and tailings management, where precise flow control ensures efficiency and reduces waste. Stringent water use regulations imposed by governments, coupled with mining companies' commitment to sustainability, further highlight the importance of reliable flowmeter data. Accurate measurements are crucial for maintaining water mass balance, optimizing reuse systems, and ensuring compliance with regulatory limits, which are essential for both operational performance and environmental responsibility. Advanced validation techniques, including the radiotracer methodology, significantly enhance the precision of water balance calculations, offering a robust foundation for sustainable water management in mining.

Although the radiotracer transit time methodology has been widely applied in industries such as oil and gas (Tayyib et al., 2019; Winniford and Dunkle, 2020), chemical and petrochemical industries (Pant et al., 2001), industrial-scale soakers (Pant et al., 2017), fluid catalytic cracking units (Affum et al., 2013), mixing studies in industrial processes (Adzaklo et al., 2018), thermal stratification test facilities (Pant et al., 2022), as well as in sectors like medicine (Rayudu et al., 2019; Zhang et al., 2025) and wastewater treatment (Sarkar et al., 2021), its adoption in the mineral processing sector remains limited. In mining, most radiotracer studies have focused on residence time distribution measurements (Lelinski et al., 2002; Yianatos et al., 2017; Vinnett et al., 2022; Vinnett et al., 2023; Vinnett et al., 2024), with less emphasis on flow measurement, particularly under the complex conditions of mineral processing. These operations involve diverse flow regimes, challenging environmental conditions, and intricate process interdependencies, all of which require robust and adaptable methodologies. Despite its potential, the use of radiotracer methodology for flow rate measurement in mining remains underexplored, especially in real-world industrial scenarios. This gap is particularly evident in industrial practice, where the limited availability of comprehensive flow data hinders the broader adoption and integration of radiotracer methods into process optimization and decision-making frameworks.

This study demonstrates the versatility of the radiotracer methodology through three key industrial validation examples in mineral processing operations. These include adjusting flow meters in leaching processes, evaluating a NaHS loop piping circuit in a molybdenum flotation plant, and validating flow meters to assess the hydraulic behavior of recirculation pumping stations for water balance quantification. These case studies underscore the methodology's effectiveness in addressing diverse challenges under real-world mining conditions.

The novelty of this research lies in the adaptation and validation of the radiotracer methodology for measuring flow rates in the complex and dynamic environments of mineral processing. By addressing critical gaps in the literature and demonstrating practical applications for precise and reliable flow measurements—achieving certified uncertainties around 1%—this study offers a robust methodology for generating accurate and reliable data to meet the rigorous demands of Mining 4.0.

2. Materials and methods

2.1. Materials

- **Radiotracer**: The study used Br-82, a radioactive isotope with a half-life of 36 hours, chosen for its favorable chemical and physical properties (IAEA, 1983; IAEA, 2001; ISO 2975-7:1977). Br-82 was prepared from irradiated potassium bromide (KBr) at the Chilean Commission of Nuclear Energy's nuclear reactor (5 MW thermal reactor, neutron flux of up to $5 \cdot 10^{13}$ n/cm²s, spatially homogeneous in 4π).

- **Detectors**: 1"x1.5" NaI (Tl) scintillation detectors (Saphymo, Montigny-le-Bretonneux, France) were employed. The detectors were collimated to focus on tracer radiation, minimizing interference from other sources.
- **Data acquisition systems**: Two data acquisition systems were utilized, enabling simultaneous data collection at up to 12 control points per system. The systems achieved a measurement time of less than 2 milliseconds to capture the rapid transit of flows.

2.2. Methods

2.2.1. Flow validation

Flow validation is critical for ensuring accurate flow meter measurements. There are three primary methods available:

1. Weighting of liquids using a weighting tank: This method involves measuring the weight of liquids using a tank truck and a truck scale (ISO 4185). While effective, it is impractical for larger flows due to logistical challenges.
2. Piston Provers: This method measures the time required to collect a known volume of liquid into a piston cylinder. It is widely used in the petrochemical industry, but it is costly and labor-intensive, requiring the flow to be directed through a separate cylinder container.
3. On-Site Validation using Tracers: This technique includes two main sub-methods: the dilution method (ISO 9555-1:1994) and the transit time method (ISO 2975-7:1977). Both can be implemented in a non-intrusive manner and do not require changes to process operations.

2.2.2. Radiotracer methodology

Injection procedure: A carefully measured pulse of radioactive liquid (Br-82 solution), approximately 3 mL in volume with a radiation activity of 10 mCi, was injected directly into the flow stream at a designated injection point. The tracer's volume and activity were optimized to ensure sufficient downstream detectability while minimizing any potential disruption to the process. The activities were estimated to achieve adequate signal-to-noise ratios, considering typical local background levels of 10–20 counts per second.

Detection procedure: Radiation levels downstream were measured after the tracer achieved complete mixing with the fluid. Pairs of NaI (Tl) scintillation detectors were positioned strategically to capture radiation signals at multiple points along the flow. The detectors were calibrated and collimated to focus exclusively on the tracer's radiation, minimizing interference from background sources and ensuring high measurement accuracy. Each pair of detectors was connected to data acquisition systems, enabling simultaneous recording of radiation signals.

2.2.3. Measurement of mean residence times, velocity and flowrate calculation

Radiation measurement data was corrected for radioactive decay and background radiation (IAEA 2004) according to Eq. (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 for background and radioactive decay. $I_{measured}$ is the radiation measured from the detectors, BG is the background radiation, t is the measurement time, and $t_{1/2}$ is the half-life of the radiotracer.

Mean residence times (MRTs) were calculated using the method of moments (IAEA 2001), as shown in Eq. (2).

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

where t_{exp} is the mean residence time.

The responses to the instantaneous (Dirac) injection of radiotracers in two sections of the pipe (points 1 and 2) were recorded. These responses were treated as Residence Time Distribution curves. The transit time $t_2 - t_1$ was calculated based on the difference of the MRTs at each detection point and used to obtain the velocity and flow rate (Equations 3 and 4).

$$V = \frac{d_2 - d_1}{t_2 - t_1} \tag{3}$$

$$Q = V \cdot \pi \cdot \frac{D^2}{4} \tag{4}$$

where: V is the fluid velocity and Q the flowrate. $d_2 - d_1$ is the distance between detectors and D is the internal diameter of the pipe.

2.2.4. Methodology for assessment of the NaHS loop pipeline in the molybdenum flotation plant

The molybdenum flotation plant includes a pipeline circuit that delivers NaHS from storage tanks to the flotation cells. The flotation cells are named as the Rougher, Cleaning, and Wemco stages (the latter being backup cells located outside the plant). Any excess NaHS is returned to the storage tanks via the return pipeline. Fig. 1 provides a diagram of the molybdenum flotation plant.

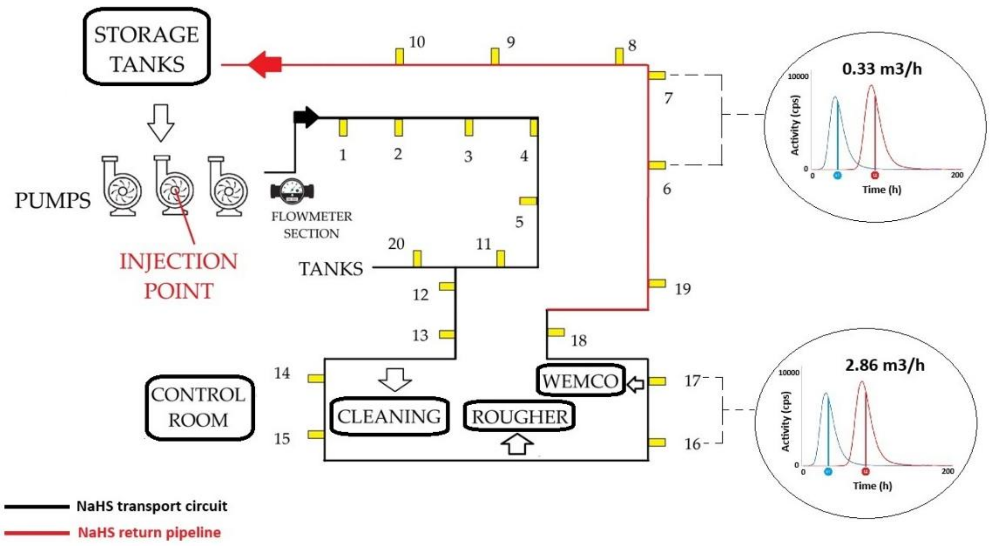

Fig 1. Diagram of the molybdenum flotation plant operation. The NaHS loop piping circuit, illustrated with black and red lines, transports NaHS from the storage tank to the flotation cells, while excess NaHS is returned through the red-marked return pipeline. Twenty gamma radiation detectors were positioned at the designated yellow squares, with the radiotracer injection point indicated. Detectors ranging from 1 to 12 were connected to the first data acquisition system, while detectors 13 to 20 were connected to the second data acquisition system. Additionally, examples of velocity data for detector pairs 16-17 and 6-7 are included to illustrate the measurement process.

3. Results and discussion

3.1. Flow meter adjustment in a leaching process plant

The solvent extraction and electrowinning (SX/EW) process is a multi-stage hydrometallurgical method used to recover ions, such as copper, from low-grade leach solutions. Precise flowmeter control is critical for maintaining stable operations and optimizing performance. Inaccurate flow data can result in discoordinated actions, reducing the effectiveness of the process.

For instance, incorrect flow measurements can lead to imbalanced reagent addition, either reducing ion recovery efficiency or increasing costs due to excess reagent use. Mismatched flow rates between interconnected tanks may cause overflows or starvation, interrupting the process. Similarly, unstable electrolyte flow in the electrowinning stage can lead to uneven metal deposition, compromising product quality. In the solvent extraction phase, poor phase mixing caused by flow inconsistencies reduces ion transfer efficiency.

These discoordinated actions create instability across the SX/EW process, increasing operational costs and reducing performance. This highlights the necessity of validating and adjusting flowmeters to ensure accurate mass balances and reliable operations.

Conventional flow meters installed in pipelines can fail due to corrosion, fouling, and the presence of elements such as acids, salts, and suspended solids. Radiotracers can be used to track the liquid phase and validate flow meters (IAEA, 2001). Table 1 compares the data obtained from deviated conventional flow meters with the radiotracer measurement standard, presenting the percentage difference between the two methods.

On-site validation results indicate that only 36% of flow measurements fell within the desired 5% error range, highlighting that most flow meters (64%) required adjustments to improve accuracy. These findings emphasize the critical importance of regular calibration and validation of flow meters to ensure the reliability of data. Radiotracers have proven to be a reliable standard for measuring flow and velocity in pipelines, providing accurate and consistent results with certified uncertainties around 1%.

This study's results align with the foundational work by Cooper (Cooper, 1987), which demonstrated the effectiveness of radiotracer techniques for fluid flow measurement and flowmeter calibration. Cooper emphasized the high sensitivity and reliability of radiotracers in detecting deviations in flow rates and validating flowmeters, particularly under challenging industrial conditions. The current findings extend this understanding to modern mineral processing applications, where the dynamic and complex flow environments demand advanced validation techniques like those provided by radiotracers.

Table 1. Flowmeter data validation using the radiotracer transit time method. The validation results are categorized as follows: Green (0-5%) indicates low error, Orange (5-8%) indicates medium error, and Red (≥8%) indicates high error. The table includes various leaching solutions used in the leaching process. These solutions correspond to different types of materials being processed in the leaching plant. Note: flow rates are presented in liters per minute (l/min) instead of cubic meters per second (m^3/s) because the values in m^3/s are too low for practical purposes (e.g. 7 l/min is equivalent to 0.000117 m3/s). Using l/min provides more easily interpretable numbers

Liquid Solutions	Inner diameter (m)	Radiotracer Mean Velocity (m/s)	Radiotracer Flow Rate (l/min)	Meter Flow Rate (l/min)	Percentage of difference between methods (%)
Rich 1 Sulfures	0.327	1.530	7.710	8.145	-5.650
Rich 2 Oxides	0.397	1.590	11.790	10.520	10.740
Rich 3 Gravel	0.353	1.420	8.320	8.581	-3.140
Refine 1 Sulfures	0.384	1.282	8.900	8.123	8.720
Refine 2 Oxides	0.441	1.360	12.440	11.708	5.890
Refine 3 Gravel	0.397	1.240	9.191	9.392	-2.190
ILS 1 Sulfures	0.409	1.520	11.994	12.394	-3.340
ILS 2 Sulfures	0.555	1.040	15.107	14.865	-1.600
ILS 3 Gravel	0.555	0.582	8.454	7.917	6.350
Organic SX-1	0.290	2.300	9.115	9.802	-7.530
Organic SX-2	0.313	2.520	11.619	13.680	-17.54

3.2. Evaluation of a NaHS loop piping circuit in a molybdenum flotation plant

Molybdenum is often recovered as a byproduct of copper mining, where selective flotation processes are used to separate copper and molybdenum into distinct concentrates. Sodium hydrosulfide (NaHS) solution plays a critical role in this process, acting as a depressant that selectively suppresses copper minerals, such as chalcopyrite ($CuFeS_2$), while allowing molybdenum minerals, like molybdenite (MoS_2), to float (Park et al., 2020).

Managing NaHS consumption is essential, as it represents approximately 20% of the total cost of molybdenum production (Diaz et al., 2022). In most plants, NaHS dosing is manually controlled based on flow meter readings and operator judgment. However, flow meter accuracy often declines over time due to continuous exposure to harsh operating conditions, such as high pressures, corrosive environments, and temperature fluctuations.

To maintain precise flow measurements, regular validation is essential to ensure accurate readings and proper tracking of NaHS usage. Radiotracers offer significant advantages in this context. Unlike conventional calibration techniques, radiotracer methods are non-intrusive and can be applied directly under operating conditions without disrupting the process. In closed piping circuits, radiotracer methodologies can achieve uncertainties of approximately 1%, even in complex systems such that the transportation of oil (Gonçalves et al., 2021). Furthermore, radiotracers enable detailed diagnostics, such as identifying flow anomalies, dead zones, or blockages, which may otherwise go undetected with traditional methods.

During the operation of a molybdenum flotation plant, it is often necessary to assess the performance of the NaHS piping circuit. This involves detecting any flow assurance issues and validating critical flow rate measurements. By integrating radiotracer methodologies into this assessment process, plants can achieve improved accuracy in flowmeter readings, leading to better control of NaHS dosage, reduced chemical waste, and optimized production costs. These benefits highlight the potential of radiotracers to enhance efficiency in molybdenum flotation operations.

3.2.1. Piping circuit characterization

Fig. 2 shows the raw data for velocity calculation between detectors 1 and 2 in Fig. 1. The velocity was determined from the average time calculated using Eq. 2. Flow rates were then derived from the velocity and cross-sectional area, with the pipe having a nominal diameter of 3 inches (0.0762 m). Table 2 presents the velocity and flow rate values for the detection points indicated in Fig.1. These values were calculated using Eqs. 3 and 4, respectively.

Pipeline flow assurance was confirmed as data showed no signs of blockages in the NaHS loop pipeline, with values consistent with the pipe diameter. Additionally, the pipelines feeding the rougher distribution containers exhibited no flow issues. The distribution containers and rougher pipelines accounted for 21% and 72% of the total flow, respectively. Furthermore, 7% of the NaHS flow returned to the storage tanks, indicating that 93% of the NaHS flow was utilized during plant operations.

The utilization rate of 93% aligns with acceptable operational limits. The return flow (7%) is an intentional feature of the loop piping circuit, serving as a critical component for maintaining system stability and operational flexibility. This design ensures consistent pressure and flow, acts as a buffer against demand fluctuations, and prevents overconsumption by recirculating excess NaHS back to the storage tanks. Maintaining the correct NaHS dosage is essential for achieving optimal sulfidity levels in the pulp, which is critical for the effective depression of copper and the selective flotation of molybdenum.

Increasing NaHS usage further may provide limited benefits while posing risks of over-saturation, potentially causing imbalances in sulfidity levels that reduce process selectivity and unnecessarily increase reagent consumption. Overuse of NaHS could also disrupt the chemical equilibrium of the flotation process, including critical parameters such as pH levels. Such disruptions can hinder the efficiency of flotation reagents, compromising the selective separation of molybdenum and copper. Any adjustments to the system should carefully account for the functional role of the return flow, which ensures system stability, maintains chemical balance, and supports optimal flotation performance.

The circuit flowmeter was validated, as summarized in Table 3, which compares radiotracer data with flowmeter readings and calculates the percentage difference. The flowmeter in the NaHS pipeline showed a mean difference of -4.8% relative to the radiotracer measurements, remaining within the plant's acceptable limit (≤ 5%).

Initially, the molybdenum plant considered making a significant investment to replace the entire pipeline circuit. However, the measurements and analysis revealed areas of uneven flow distribution, such as in Sections 6-7 in Table 2, where certain pipeline segments exhibited notably lower velocities. Despite these irregularities, the pipeline was confirmed to be free of obstructions. Additionally, a leak was detected in one of the valves, contributing to the uneven flow distribution. This finding highlights the versatility of radiotracer methodologies, which are well-supported for leak detection in industrial systems. As noted by Rao (Rao, 1987), radiotracers are particularly effective for locating leaks in pipelines, offering a reliable "Yes or No" diagnostic approach. This capability was instrumental in diagnosing the issue.

To address these findings, several recommendations were made to improve process performance. These included checking a few valves to ensure proper operation, conducting regular assessments of pipeline flow assurance and integrity, and systematically recording historical data to support informed decision-making. This proactive approach enabled the plant to avoid the substantial cost of replacing the pipeline, instead focusing on targeted improvements to enhance the efficiency and reliability of the pipeline circuit.

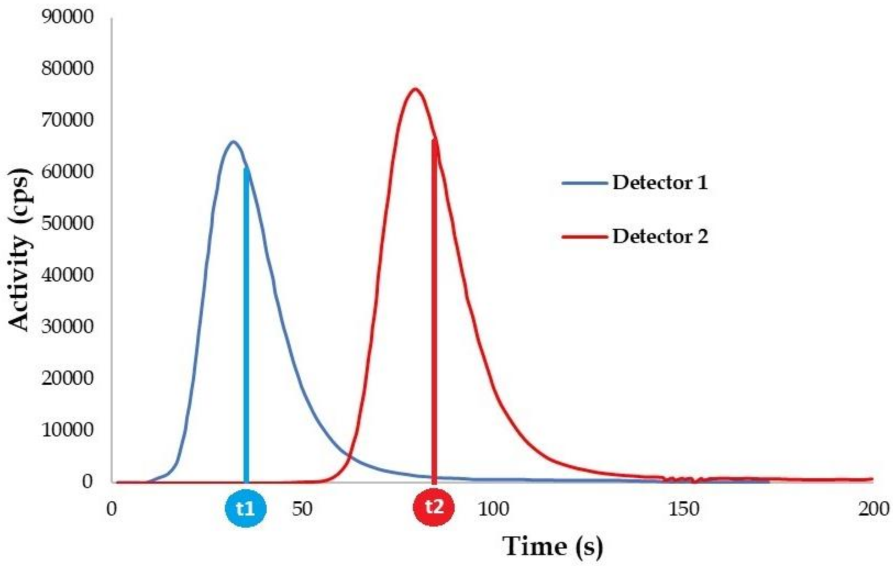

Fig. 2. Velocity is calculated based on the transit time between detector positions. The radiation activity data, measured in counts per second, considers the distance between the center of mass of the curve detected by detector 1 and the center of mass of the curve detected by detector 2

Table 2. Radiotracer-derived velocity and flow measurements for each detection point in the pipeline circuit

Detector location	Transit time (s)	Distance (m)	Radiotracer Flow Velocity (m/s)	Radiotracer Flow Rate (m^3/s)
1-2	45.360±0.030	14.670	0.323±0.002	5.303
2-3	47.670±0.020	14.500	0.304±0.002	4.991
3-4	34.360±0.020	10.180	0.296±0.002	4.859
4-5	39.960±0.020	12.100	0.303±0.002	4.925
6-7	264.700±0.800	12.100	0.046±0.000	0.331
7-8	222.000±2.000	10.180	0.046±0.000	0.334
8-9	302.000±2.000	14.500	0.046±0.000	0.350
9-10	316.000±2.000	14.670	0.047±0.000	0.339
11-12	21.150±0.030	5.800	0.323±0.002	4.500
12-13	51.300±0.020	9.000	0.304±0.002	2.870
13-14	152.920±0.090	26.400	0.296±0.002	2.840
14-15	110.780±0.060	19.650	0.303±0.002	2.910
15-16	189.200±0.100	31.000	0.046±0.000	2.690
16-17	107.650±0.080	18.750	0.046±0.000	2.860
17-18	36.550±0.060	6.300	0.048±0.000	2.820
18-19	172.000±0.300	10.150	0.047±0.000	0.970
11-20	185.700±0.010	12.900	0.070±0.000	1.140

Table 3. Comparison between flowmeter data and radiotracer-derived velocity measurements. Green (0-5%) indicates low error, and Orange (5-8%) indicates medium error

Test	Radiotracer velocity measurements (m/s)	Radiotracer flow rate value (m^3/h)	Flowmeter value (m^3/h)	Difference between flowmeter and radiotracer method (%)
1	0.30	4.91	5.22	-6.30
2	0.31	5.02	5.16	-2.80
Mean	0.30	4.95	5.19	-4.80

3.3. Validation of flow meters to assess the hydraulic behavior of recirculation pumping stations for water balance quantification

Water scarcity in arid regions presents significant challenges for mining operations, which rely heavily on water for processes like flotation, dust suppression, and tailings management. Efficient water management and precise water balance quantification are essential for sustainability and regulatory compliance. Validating flow meters ensures accurate readings, enabling optimization of recirculation pumping stations and efficient water distribution.

The objective of this showcase example was to characterize the hydraulic behavior of the recirculation pumping stations for industrial water at the mine, to establish a reliable mass balance of water, considering the feeding systems, pumping stations, and water recirculation channels. This involved measuring velocities and flow rates in each pipe and pumping station.

Table 4 presents the average flow velocities and standard deviations (in m/s) in lift stations in a mining site in northern Chile, measured using the radiotracer method. The low standard deviations, ranging between 0.01 and 0.05 m/s, indicate consistent and reliable flow velocity measurements across different stations. These measurements provide valuable insights into the hydraulic behavior of the recirculation pumping stations, identifying specific areas where adjustments or enhancements can improve overall system efficiency and reliability.

Table 4. Average flow speeds and standard deviations in lift stations using the radiotracer method

Pumping station	Flow condition	Average flow velocity [m/s]	Standard Deviation [m/s] n=3 [±]
Alto 1	One pump operating	0.9	0.01
Alto 2	Three pumps operating	1.72	0.01
Alto 3	Two pumps operating	1.88	0.01
Drains Valle	One pump operating	0.41	0.01
Fija to Plant	One pump operating	0.47	0.01
Station B2	Five pumps operating	2.22	0.08
Tank 052	Six pumps operating	2.49	0.05
Ventana Two	Only gravity	0.77	0.01
Drain Sierra	One pump operating	0.56	0.01
Station A1 (Sierra)	Three pumps operating	1.58	0.02
Intermediate to A1	Six pumps operating	1.76	0.04
Intermediate to Tank 14	Five pumps operating	1.08	0.05

3.3.1. Flow comparison between radiotracer measurements and online flowmeter measurements

To validate the accuracy and reliability of flowmeters used in the recirculation pumping stations, a comparative analysis was conducted between measurements obtained using radiotracers and those obtained from the online flowmeters. This comparison helps to identify any discrepancies and ensures that the flowmeters provide accurate data for effective water management. Table 5 presents the flow comparison between radiotracer measurements and online flowmeter measurements. The deviations observed between radiotracer measurements and online flowmeter measurements, ranging from 6.91% to 22.55%, highlight the critical need for flowmeter adjustments.

Table 5. Flow comparison between radiotracer measurements and online flowmeter measurements. Orange (5-8%) indicates medium error, and Red (≥8%) indicates a high error

Pumping station	Nº of operating pumps	Flowmeter [m^3/s]	Flow with radiotracers [m^3/s]	Difference between flowmeter and radiotracer method (%)
Alto 1	1	0.232	0.217	6.91
Alto 1	2	0.385	0.335	14.93
Alto 1	3	0.467	0.412	13.35
Drains Valle	1	0.079	0.102	-22.55
Drains Valle	2	0.164	0.207	-20.77
Drains Valle	3	0.224	0.278	-19.42

Inaccurate flow measurements can lead to erroneous calculations of water usage, directly affecting the operational efficiency of mining processes such as flotation and tailings management. Overestimating or underestimating water flow can result in wastage or insufficient water supply, respectively. Poor water management practices stemming from inaccurate flow data can also lead to regulatory non-compliance, potentially causing environmental harm and incurring fines. Ensuring precise validation and/or calibration of flowmeters is thus essential for maintaining accurate water balances and optimizing resource use in mining operations.

The use of radiotracers for flow validation, as demonstrated in this case example, aligns with the findings of Díaz et al. (2016), who conducted a similar study at Los Pelambres Mine in Chile. Their research demonstrated the effectiveness of combining fluorescent tracer dilution and radioactive tracer transit time methods to measure flow rates and velocities in pipes affected by scaling issues. This approach enabled accurate assessment of internal pipe diameters and the identification of miscalibrated flow meters, ultimately leading to enhanced water management practices.

4. Conclusions

This study underscores the critical role of accurate flowmeter data in optimizing mineral processing operations. The validation of flow meters across three key areas yielded several significant insights:

1. Leaching Processes: Flowmeter control is crucial for optimizing performance and maintaining precise mass balances. On-site validations revealed that only 36% of the measurements fell within the acceptable error margin of 5%. This finding highlights the importance of continuous monitoring and regular validation to ensure reliable flow data.
2. NaHS Loop Piping Circuit: Accurate, data-driven decisions allowed the plant to avoid unnecessary pipeline replacements, focusing instead on process improvements such as optimizing flow distribution, adjusting flow rates, and performing routine maintenance. A mean difference of -4.8% between flowmeter and radiotracer values, while within acceptable limits, reinforced the need for ongoing validation to maintain data reliability and process efficiency.
3. Recirculation Pumping Stations: Deviations between radiotracer measurements and online flowmeter readings (ranging from 6.91% to 22.55%) revealed the necessity of calibrating and adjusting most flow meters. Accurate flow measurements are essential for maintaining precise water balances, ensuring regulatory compliance, and supporting sustainable water management practices.

This study underscores the importance of accurate flowmeter validation in supporting operational efficiency, sustainability, and compliance within the mining sector. Several key findings emerged:

1. Critical Importance of Flowmeter Accuracy: Across all three case studies, accurate flowmeter readings proved essential for optimizing performance, maintaining mass balances, and supporting sustainable water management. Deviations between flowmeter and radiotracer measurements highlighted the need for routine validation and recalibration to ensure reliability.
2. Value of Radiotracer Methodology: The radiotracer transit time method demonstrated exceptional utility in identifying flow anomalies, miscalibrated flowmeters, and areas for process improvement. Its non-intrusive nature and high accuracy, even in complex and dynamic systems, make it a valuable tool for validating flowmeters under real-world operating conditions.
3. Data-Driven Decision-Making: Accurate data allowed the molybdenum plant to avoid unnecessary expenditures, such as replacing the pipeline circuit. Instead, targeted improvements, including valve adjustments and flow distribution optimization, addressed the identified issues, showcasing the importance of informed, data-based decision-making.
4. Alignment with Sustainability Goals: The study's emphasis on efficient resource use and sustainable water management aligns with global objectives like the United Nations Sustainable Development Goals (SDGs), particularly Goal 6 (Ensure Access to Water for all) and Goal 12 (Responsible Consumption and Production). These findings contribute to the development of resilient and sustainable industrial practices in water-scarce regions.

Future research and industrial applications should focus on the following areas:

- Advanced Monitoring Technologies: While radiotracer methods provide precise, discrete flow data under specific operational conditions, historical radiotracer data can be effectively integrated with real-time flowmeter systems to enhance overall flow measurement accuracy. Radiotracers can serve as critical benchmarks for periodically validating and calibrating online flowmeters, ensuring their reliability over time. Machine learning and data analytics can further leverage historical radiotracer data to detect patterns, predict flowmeter drift, and optimize maintenance schedules. A hybrid monitoring system, combining periodic radiotracer validation with continuous online flowmeter monitoring, offers a practical solution for improving long-term process optimization.
- Expanded Industrial Applications: Radiotracer methodologies have demonstrated their value in various industrial contexts and should be explored further in mining processes such as heap leaching, slurry transport, and tailings management, where flow accuracy is critical. For example, using radiotracers to evaluate flow consistency in slurry pipelines could significantly reduce blockages and optimize material transport.
- Regulatory Integration: The ISO 2975-7:1977 standard for radiotracer-based flow measurement provides clear guidance but is largely unknown to high-level executives in the mining industry. Without their awareness, the methodology cannot gain widespread adoption. Promoting the standard among senior management would ensure accurate flow measurements, improved process optimization, and stronger regulatory compliance.

In summary, this study highlights the value of radiotracer methodologies in improving flowmeter accuracy and supporting efficient water management in mining. The findings emphasize the importance of adopting innovative technologies to achieve operational excellence in modern mining.

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