Future (and Present) Trends in Flotation Circuit Design

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ABSTRACT

The conventional approach to flotation circuit design has undergone a number of developments in the past decade. The need to maximise recovery and value when processing low-grade orebodies at high throughput presents a number of challenges. For example, improving both fine and coarse particle recovery, footprint and layout constraints, as well as managing CAPEX/OPEX, are driving innovations in cell selection, design, sizing and duty.

Economies of scale have traditionally been achieved by the installation of large mechanical cells with volumes over 600 m^3 to meet residence time requirements for high-capacity plants. However, in these large cells performance and flotation efficiency are compromised. Reduced mixing, turbulence, dead zones, greater froth travel distance to the concentrate launder plus increased chance of particle detachment back into the pulp phase limit their effectiveness.

Hatch has completed concept studies, feasibility and detailed engineering designs for several flotation technologies which are setting new standards for circuit design and performance. This paper describes the piloting, modelling, and engineering required to install the largest Jameson Cell developed for a rougher-scalping duty, as well as evaluation of Jameson Cells not only in cleaner stages (their traditional use) but also in pre-flotation and scalping duties. The paper also covers engineering design of coarse particle flotation circuits, including experience with conceptual studies, test work and detailed design to apply the Eriez HydroFloat™ to coarse tailings scavenging.

Finally, the evaluation and application of small footprint and fast flotation kinetics cells such as Eriez StackCell®s, Woodgrove Staged Flotation Reactor (SFR) and Direct Flotation Reactor (DFR) is discussed.

INTRODUCTION

Flotation machine manufacturers have historically focused on increasing cell size, with cell volumes increasing from 100 to over 680 cubic meters in the past 20 years. This increase has been driven mainly by the desire for fewer, high-capacity cells, resulting in a simplified plant layout and reduced maintenance. An overall decline in orebody head grades has also resulted in higher plant throughput, and thus larger equipment sizes, to maintain metal production. Unfortunately, larger cells require increased energy input to maintain particles in suspension. The increased energy input results in greater turbulence which is a major contributor to the loss in recovery of coarse particles. Likewise, the size and reduced number of cells in series can result in an increase in by-pass or short-circuiting of material; with a detrimental effect on the slow floating mineral particles (i.e., fines). Although larger mechanical cells reduce flotation circuit footprint compared to smaller volume alternatives, the fact remains that tank cell circuits still occupy a significant area, which can be a challenge for layout constrained sites e.g., in mountainous regions. They also require significant investment in civil/structural design and foundations to support the large masses, often at height to enable gravity flows.

Large cells are more energy efficient in that the total energy per unit volume is reduced, however, high specific energy input is required to improve the flotation kinetics of fine and/or slow-floating particles. Larger cells are more difficult to sample representatively and inspect, impacting their ability to be run optimally. Management of froth transport parameters can also be challenging, with smaller numbers of large cells experiencing significant step-change in concentrate mass and mass pull down the bank, meaning that each cell must be assessed individually for lip loading and froth carrying capacity with tailored launder configurations and froth crowding. Finally, with the need to process more complex orebodies, combined with the coarse and fine particle recovery optimisation challenges mentioned above, tank cell circuits often involve one or more recirculating streams to improve recovery. However, this is a sub-optimal arrangement, mixing streams of different particle classes or sizes (or floatability) means that it is often challenging to optimise the circuit to target improved recovery of a particular size-by-mineral class.

Over the last 10 years, the industry has seen the development of several new types of flotation cells, applying fundamental flotation principles to address the issues identified above, such as pneumatic cells with froth wash water for improved fines recovery and entrainment reduction, fluidised bed cells and energy efficient stage flotation cells. Furthermore, some new cell designs have occurred recently that are yet to be readily applied in industry but offer significant potential, such as the Jord International's NovaCell and FLSmidth Reflux Flotation Cell

This paper will examine the potential that various flotation technologies offer for improving both fine and coarse particle recovery, meeting footprint and layout constraints, as well as managing CAPEX/OPEX, and increasing constraints on energy and water consumption. Three key areas will be discussed including pneumatic cells, such as the Jameson Cell being applied in rougher/rougher-scalper duties for Cu/Au and Au operations. Secondly, the design and modelling of coarse particle flotation circuits based on recent Hatch projects in concept, PFS and Detailed Design/Execution project phases will be examined. Finally, opportunities for energy-efficient, small footprint cells, particularly for increasing rougher capacity in brownfields expansion projects will be detailed. These experiences will be used to highlight the authors expectations for future flotation circuit design trends, some of which are already occurring today.

NEW TECHNOLOGIES FOR FLOTATION CIRCUIT DESIGN

Manufacturers of conventional flotation cells continue to refine the design of their rotor-stator mechanisms for improved fine and coarse particle flotation. These improved designs aim to improve solids suspension, gas dispersion and bubble-particle attachment. Some examples of impeller-stator mechanisms are the nextSTEP™ of FLSmidth and FloatForce of Metso:Outotec. These mechanisms can also be retrofitted to existing flotation cells. For finer particles, a mechanism one size smaller than normally selected can be used at higher speed. For coarse particles, a larger mechanism at lower speed will provide sufficient mixing while minimising high turbulence.

Alternative technologies have been developed with the goal of providing more efficient flotation, including multi-chamber mechanical machines supplied by Eriez (StackCell®) and Woodgrove

(Staged Flotation Reactor, SFR, and Direct Flotation Reactor, DFR). These devices build on the concept of focused energy input to enhance fine particle and relatively coarse particle (DFR) recovery as well as improving flotation kinetics. This novel approach decouples the particle contacting and collection zone within the cell from the froth phase separation zone. As a result, overall unit size can be reduced while maintaining the same capacity and metallurgical performance. It is worth mentioning that these flotation machines are not sized based on residence time. The implications of this step-change in technology are numerous and include a significant reduction in energy consumption (> 40%) as well as reductions in plant height, footprint and foundation loads of greater than fifty percent. One notable installation of these cell types is the Woodgrove SFR cells installed for the BHP Spence Growth Option concentrator project which involves 78 SRF cells for both Cu and Mo flotation as the operation transitions from oxide to sulphide processing (Heffernan, 2018). This circuit commenced operation in May 2022 and had a 50% reduced footprint and 60% lower energy consumption compared to a conventional tank cell circuit of similar capacity (BHP, 2022).

Another alternative technology that provides more efficient flotation is pneumatic flotation, examples include the Jameson, Concorde, Imhoflot and Reflux flotation cells. These cells do not use an impeller like mechanical cells. Rather, the air and pulp are mixed in a continuous stream of high fluid velocity through a downcomer or venturi to disperse the air into fine bubbles and maintain particle suspension. Froth wash water is often used to enhance concentrate grade, minimizing recovery by entrainment. There has been a growing application of these types of cells, not only in cleaner stages (their traditional use) but also in pre-flotation and scalping duties (Hassanzadeh et al, 2022).

The authors have recently been involved in the evaluation and detailed design of circuit expansion options involving the addition of Jameson Cells in rougher-scalper duty to gold operations in Russia and Cu-Au concentrator in Australia. Glencore Technology has recently launched the Jameson Concentrator, a flexible combination of Jameson Cell & IsaMill technology that can comprise an entire flotation circuit (roughing, scavenging & cleaning stages) as well as regrinding. This approach uses fast kinetics Jameson Cells with adjustments to wash water, froth depth and vacuum pressure to operate the cell effectively in all duties and significantly reduce plant footprint and energy consumption (Harbort, 2019). A full Jameson Cell concentrator is installed at Hudbay' s New Britannia Cu/Au operation in Canada and in the near future another flotation circuit comprising solely of Jameson Cells will be installed at the Ozernoye lead/zinc greenfield in Russia, with the authors being involved in the initial phases of the development of the latter.

There is also an increasing demand for coarse particle flotation as this would lead to a reduction in energy demand in preceding comminution stages and increase production rates. For example, if flotation could be performed at a P_{80} of 300 µm rather than 100 µm, the potential energy savings in comminution would be around 30 – 50 %. Coarser grind sizes also have the potential to significantly reduce operating costs for power and grinding media. They also result in coarser tailings streams creating certain operational advantages and cost reductions at sites that incorporate sand embarkments (dry stacking), tailings filtration or paste backfill.

The reduction in recovery for coarse particles is often attributed to detachment due to excessive turbulence within conventional mechanical flotation cells. Poor liberation can also create challenges when treating coarse particles. The low degree of liberation for particles coarser than 150 µm can reduce the strength of bubble/particle aggregates. This condition reinforces the need for a non-turbulent flotation environment to maximise coarse particle flotation (Kohmuench. et al, 2018). The limitations of conventional flotation machines can be overcome through the utilisation of a fluidized-bed flotation machine specifically engineered for the selective recovery of feeds containing very coarse particles. The HydroFloat™ separator, designed in the early 2000s, and initially used in industrial minerals applications, addresses the limitations of traditional flotation systems (Kohmuench et al., 2001). By using a quiescent, aerated fluidised bed, the turbulence commonly found in a mixed-tank contacting environment is greatly minimized. As a result, delicate bubble-particle aggregates are more likely to report to the concentrate without disruption. The absence of a continuous froth phase minimizes drop back that can occur at the pulp/froth interface (Kohmuench et al., 2018). Furthermore, the HydroFloat™ operates most effectively with a feed tailored to a narrow size range, typically this is a top to bottom size ratio of 5:1, requiring effective feed preparation circuit design as detailed later in this paper. The NovaCell™, by Jord International is a recently commercialised cell that uses a combination of feed injection via a downcomer and froth phase for fine particle recovery with a fluidised bed zone to simultaneously enable the recovery of coarse particles in a single flotation device.

The diagram shown in FIG 1 highlights the main alternative flotation technologies and recent developments in flotation in orange.

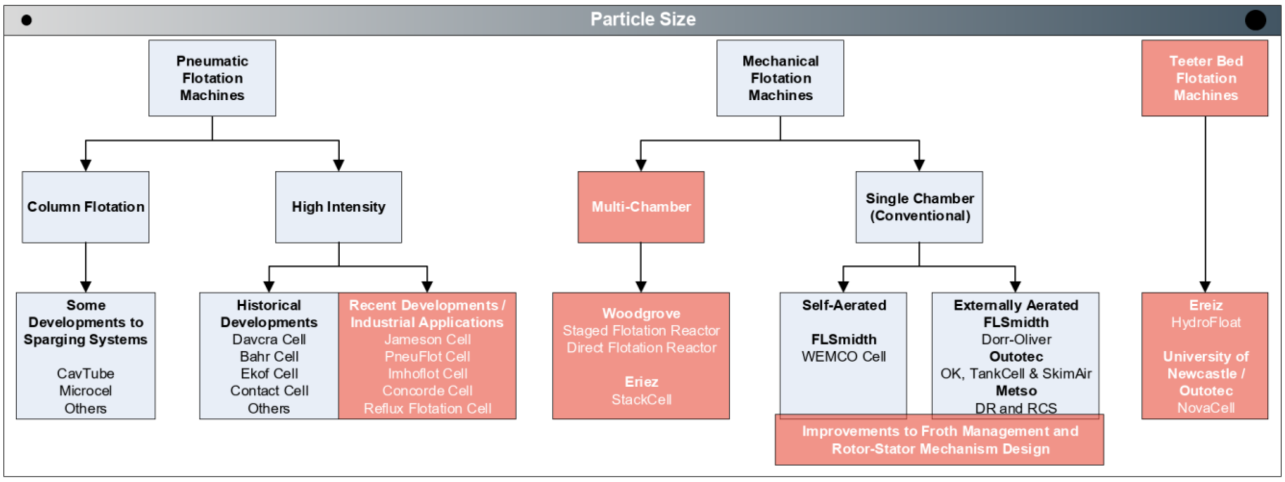

FIG 1 – Flotation machine types

With the suite of alternative flotation technologies available, the authors recognise that one area for continued development is the laboratory testwork required to simulate cell performance and its translation to modelling. Batch and locked cycle test procedures for predicting mechanical cell and circuit performance are well-established and conducted by laboratories, companies and universities worldwide. These are generally accepted as predictors of any mechanical tank cell performance, independent of designs specific to each vendor. The same cannot be said for the suite of alternative and emerging technologies. Some laboratory scale procedures exist, such as three-stage dilution test for Jameson Cells, but generally vendor specific piloting is required to produce performance data for modelling (e.g., grade-recovery curves versus mass pull). This poses challenges for greenfield projects, where testwork is often performed using drill core samples and insufficient sample is available to conduct a suite of pilot tests. It also compromises brownfield projects which may be schedule or logistics constrained and thus do not have sufficient time to organise site piloting of three or four different cell types.

JAMESON CELLS FOR NEW DUTIES

Pneumatic flotation machines were among the first machines used in flotation. However, with the advent of mechanical sub-aeration cells, the use of pneumatic flotation machines declined significantly (Harbort, 2019) There are several design types of pneumatic flotation cells. Although a variety of aerators, pulp feed arrangements, and separating vessel designs exist, the applied principles and fundamental design remain unchanged. Jameson Cells have traditionally been utilised in a cleaning duty due to their ability to produce high grade concentrates and improved fines recovery minimising losses to slimes (Hassanzadeh et al., 2022).

The first example of Jameson Cells in a roughing duty was at the Philex Cu/Au mine in the Philippines, which progressively transitioned their existing tank cell circuit to a complete Jameson Cell circuit (Roughers, Scavenger, Cleaner, Recleaner & Cleaner-Scavenger) in 1996 (Harbort et al., 1997).

Recently, the authors have been involved in optimisation projects and engineering studies to install Jameson Cells in a rougher duty for Au and Cu operations, including the development of the new Z-series cell for increased capacity.

Hatch progressed Rougher Jameson Cell design and installation through Concept, PFS, FS and Detailed Design phases for an Australian Cu-Au operation who wanted to address flotation recovery losses as part of a plant expansion. Early study phases analysed flotation circuit survey data and mass balance results which showed that the distribution of solids, gold and copper below 20 μm in the final tailings were 18%, 35%, and 20%, respectively. This was a significant imbalance, with the majority of gold and copper minerals occurring in well-liberated particles. Various options were considered to improve the recovery of these fine and ultrafine gold and copper particles which are currently lost to tailings, especially in the rougher-scavenger bank. Preliminary modelling was used to identify the most promising alternatives. The Jameson Cell in a rougher-scalper duty was shown to produce a higher Au and Cu recovery and grade, due to the generation of a fine average bubble size (0.5 mm), low turbulence (no rotor) and the presence of froth washing water. The recovery effect is expected to be particularly pronounced in the fines/ultrafine particle size range (< 20 µm).

A pilot program using an L500/1 cell, comprising 55 tests, was undertaken to determine the expected performance of the Jameson Cell in rougher-scalper duty. Results from the Jameson Cell piloting showed that:

- A fraction of the copper mineral particles (e.g., chalcopyrite) in the feed were sufficiently liberated at the current grind size P_{80} of 140 µm to allow a final grade concentrate to be produced without further grinding (for liberation improvement).
- Froth washing water in the Jameson cell significantly reduced the recovery of gangue minerals by entrainment, resulting in a substantial improvement in copper concentrate grade up to 28-30% Cu.

The grade/recovery curves from pilot testing with and without froth washing are plotted in FIG 2. The Jameson Cell can be operated with froth washing turned on to produce a final concentrate (‘scalping’ mode), or off to operate in ‘standard’ roughing mode. In the latter, unit Cu recovery (up to 80%) is greater than what is typically achieved in a single mechanical cell due to the attributes of the Jameson Cell technology (no short-circuiting, finer bubble size - 0.3-0.6 mm, and high mixing intensity). Due to the potential for future variation in ore characteristics, including variation in the liberation characteristics of the ore, and potential increased in the penalty element fluorine, the option to send Jameson Cell concentrate to regrind and cleaner circuit is maintained (i.e., rougher duty).

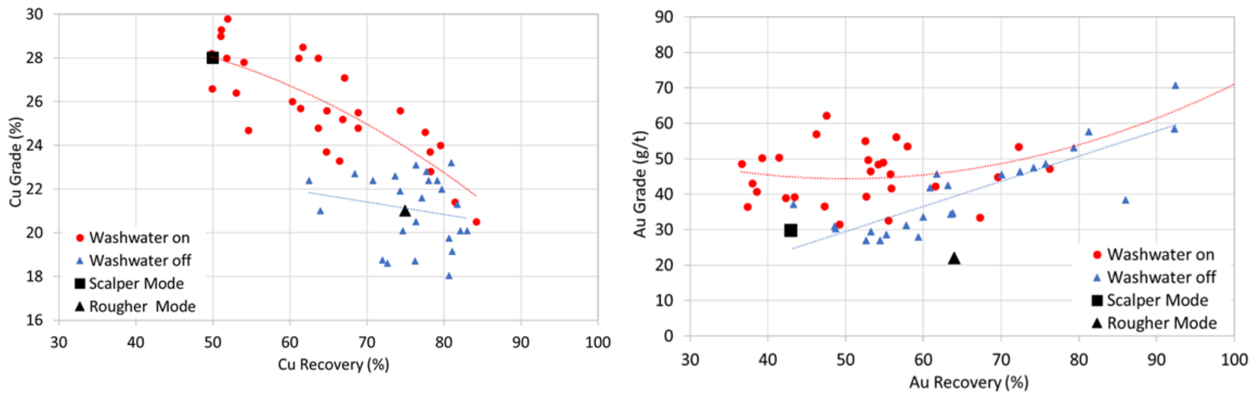

FIG 2 – Pilot L500 Jameson Cell grade-recovery curve for Cu (left) and Au (right) with Rougher and Scalper design points

Two mass balances were produced during this project for equipment design and capacity checks utilising JKSimFloat to model mass and volume flows and cell performance, as shown in FIG 3. Flotation recovery will be a strong function of the circuit arrangement, flotation bank residence times, ore floatability and cell operating parameters. Flotation modelling is a great tool for simulating these various interactive effects. Hatch uses floatability component models where the stream floatability is represented by a multi-component floatability distribution and the rate constants of these components are a function of the cell operating conditions, ore properties particle size, mineral association/liberation and pulp chemistry.

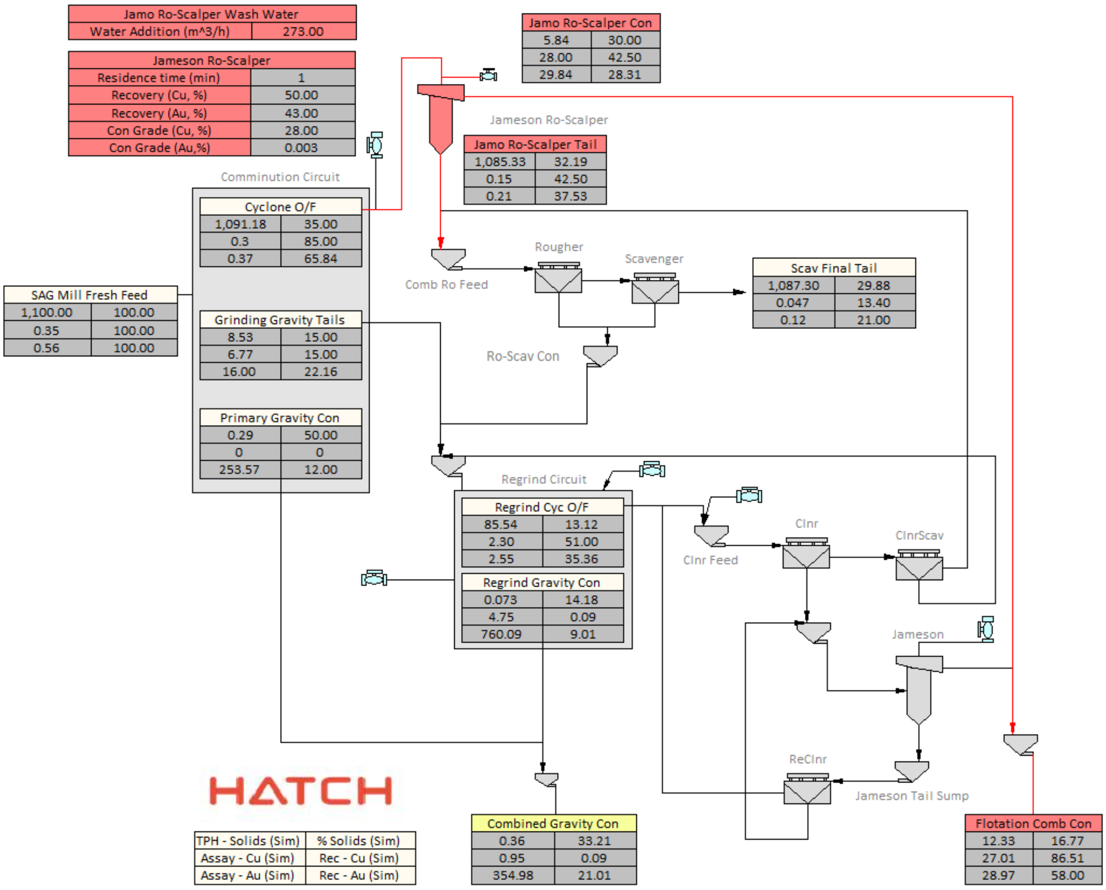

FIG 3 – JKSimFloat model for upgraded flotation circuit with Rougher-Scalper Jameson Cell

The overall recovery (R) of each mineral in each flotation bank is a function of the recovery of each of its components (R_i) weighted according to the proportion of each component in the bank feed, as shown in Equation 1 (Savassi, 1998; Runge et al., 2001). Thus, flotation recovery is also a function of the proportion of each component in the flotation feed (m_i).

$$R = \sum_{i=1}^{n} m_i \cdot \frac{C\, k_i^{batch}\, \tau\, (1-R_w)+ENT\, R_w}{(1+C\, k_i^{batch}\, \tau\,)(1-R_w)+ENT\, R_w} \qquad \text{(Eq. 1)}$$

Where: C is the scale-up factor to account for differences in cell operation between the full-scale cell in comparison to the batch laboratory flotation cell, k_i^{batch} is the flotation rate of each floatability component (i) achieved in the batch laboratory flotation test performed using standard operating conditions, R_W is water recovery, *ENT* is the degree of entrainment and τ is the residence time.

There is no widely accepted model for Jameson cells available and their metallurgical performance is often scaled up from laboratory (dilution batch flotation tests) and/or pilot plant testing by assuming fixed values for metal recovery, concentrate grade and concentrate percent solids. With the growing application of these types of cells, not only in cleaner stages (their traditional use) but also in pre-flotation and scalping duties, there is a need to predict performance more accurately for circuit design and optimization. The authors use a new approach to simulate Jameson Cell performance and its applicability has been demonstrated in different operations. This methodology has been previously published by Tabosa et. al., 2020.

Jameson cell design performance targets from the piloting campaign were established as follows:

- **Jameson Rougher**: 75 % Cu recovery at 21 % Cu grade (Cu enrichment ratio of 70), 1.1 % concentrate mass pull, 40 % w/w concentrate solids concentration with no wash water addition.
- **Jameson Rougher-Scalper**: 50 % Cu recovery at 28 % Cu grade (Cu enrichment ratio of 93.3), 0.5 % concentrate mass pull, 30 % w/w concentrate solids concentration with 273 m^3/h wash water addition.

When using fixed recovery and mass split values to simulate Jameson Cells, the product streams (concentrates and tailings) will have the same floatability distribution as the feed. This will result in unrealistic performance of the overall circuit and limits the simulations that can be performed (for example, changes in circuit reconfiguration). For more accurate simulations, it is necessary to predict the floatability distribution of the products of the Jameson Cell. A simplification to the floatability component model is used to better assess the separability of a Jameson cell in a flow sheet. The effect of residence time can be removed by assuming a fixed and short residence time of one minute in Equation 1. This simplified floatability component model allows the floatability of the feed to the Jameson cell to be redistributed, producing different floatability distributions in the concentrate and tailings streams and accounting for the impact on downstream rougher-scavenger tank cell performance. Expected ore floatability of the Jameson Rougher and Jameson Rougher-Scalper tail streams (i.e., new fresh feed to the existing rougher bank of mechanical cells) are compared with ore floatability characteristics of the original cyclone overflow feeding flotation in FIG 4. A slower copper and gold flotation kinetics stream are expected to be feeding the existing rougher bank of mechanical cells for both Rougher and Rougher-Scalper scenarios, with the increased mass pull for the rougher scenario having the larger effect on tailings floatability as expected. The flotation piloting and modelling approach utilised here allowed a single large Jameson Cell to maintain circuit recovery despite an ~30% increase in throughput, which severely impacted residence time in the rougher-scavenger bank. Moreover, the use of this alternative technology targeted specific fine Cu-Au losses and provided an option to relieve the overloaded cleaner circuit through effective use of wash water, minimising entrainment and enabling a final concentrate grade product to be produced.

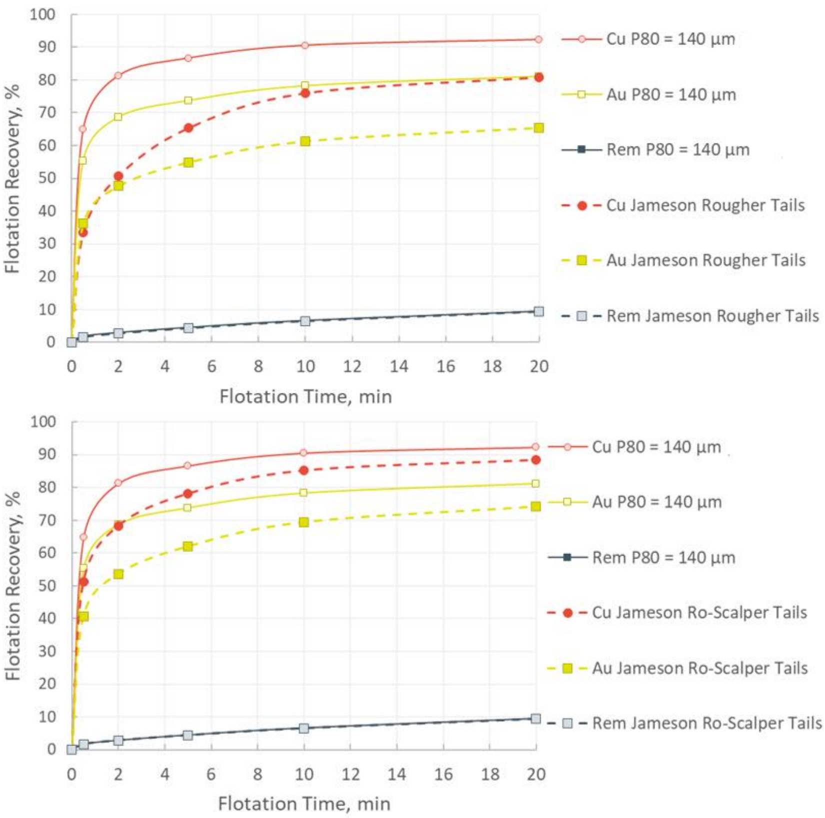

FIG 4 – Cu, Au and Remainder floatability characteristics for flotation circuit feed and Jameson Rougher (top) and Rougher-Scalper (bottom) tails

Although the application of a Jameson Cell has been presented in the above analysis, cells such as the Imhoflot G-cell offer similar potential, as shown by comparison testwork analysed by the authors for a Russian gold operation, where grade-recovery curves were produced for both cell types operating side by side in rougher-scalper and cleaner duties (FIG 5).

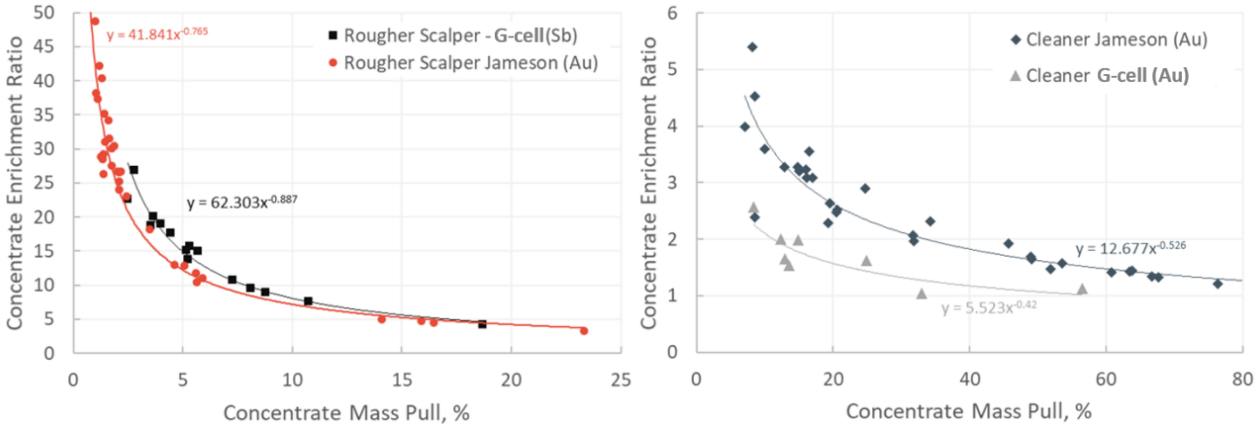

FIG 5 – Jameson Cell and Imhoflot G-cell pilot test rig mass pull verses enrichment curves

Pilot trials of the G-cell at the Kazzinc Altyntau Kokshetau operation in Kazakhstan further demonstrated the success of pneumatic cells in alternate duties - specifically the cyclone overflow stream. The 8 Mtpa gold concentrator includes crushing, grinding and coarse gold recovery via flash flotation and gravity concentration prior to flotation. The conventional tank cell circuit operates with a feed grade of 0.81 g/t Au and has a final tailings grade of 0.47 g/t, with size-by-size analysis indicating 65% of Au losses were in the <38µm fraction (Hoang, et al., 2022). Size by size pilot unit performance indicates that in this duty it was possible to recover up to 66-69% of the gold in <20 and 38µm fractions after reagent and cell parameter optimisation (FIG 6). Significantly, across the nine test conditions an average concentrate grade of 19.9 g/t Au was obtained, compared to the existing circuit final concentrate grade of 25-30 g/t achieved with two cleaning stages.

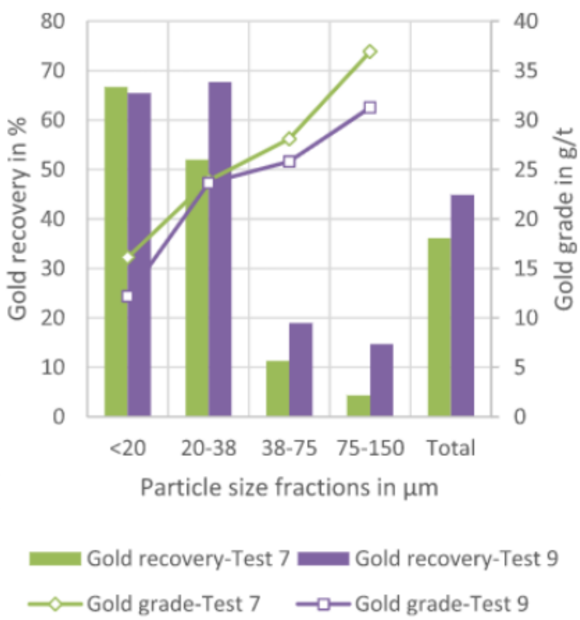

FIG 6 – Imhoflot pilot G-cell Au recovery by size and concentrate grade with optimised reagent addition (reproduced from Hoang et. al, 2022)

Overall, the various piloting and modelling results above support the theory that Jameson Cells, and similar pneumatic flotation cell types have significant potential for new, scalping duties at the head of flotation banks, where they can effectively recover fast floating, fine or well-liberated valuable minerals and also relieve capacity constraints in the downstream circuit.

COARSE PARTICLE FLOTATION CIRCUITS

Increasing throughput with fixed installed comminution energy or increasing grind size as a strategy to reduce comminution energy consumption can result in coarsening of flotation feed size and a reduction in particle liberation and recovery (Fosu et al., 2015).

Coarse particles require intensive stirring energy to suspend them and have a lower probability of particle bubble attachment due to poor liberation. In addition, the high-shear environment of a conventional flotation cell results in a higher rate of bubble particle detachment. The results is a higher representation in the tailings of a conventional flotation cell (Whitworth et al., 2022).

One technology suitable to recover coarse particles is fluidised bed flotation where the flotation cell contains a bed of particles as well as and up flow of fluidising water. Eriez' HydroFloat™ and Jord International's NovaCell™ fluidised bed flotation units are currently used for coarse particle flotation (Whitworth et al., 2022).

The Eriez HydroFloat™ cell combines hindered teeter-bed of fluidised solids with the injection of small air bubbles. to float coarse particles from a reagentised fines deficient feed. The unit contains three sections, an upper freeboard section, a middle separation section and the lower dewatering cone (Kohmenench et al., 2018).

Brownfield installations of Eriez HydroFloat™ units have been predominantly used in a scavenger duty where there is a lower risk to the existing facility. The use of coarse particle flotation technologies within the primary grinding circuit to concentrate valuable coarse mineral particles or to remove well-liberated gangue minerals in base and precious metals is still in early stages despite its promising potential.

The Jord International's NovaCell™ is an emerging coarse particle flotation technology with a cell containing a fluidised-bed and a disengagement zone. The feed is combined with a recycle stream and enters via a downcomer to the top of the disengagement zone and falls counter-currently downwards where it then forms the fluidised bed. In contrast with Eriez HydroFloat™, the NovaCell™ does not require a tailored narrow feed size distribution. Furthermore, the NovaCell™ produces both a coarse particle concentrate and a fines stream containing froth concentrate (Jameson and Emer, 2019).

There is no widely accepted model for the Eriez HydroFloat™ available, and metallurgical performance is often scaled-up from laboratory HydroFloat™ tests and/or pilot plant testing by assuming fixed values for metal recovery by size, mass recovery by size and concentrate percent solids.

Mineralogical and liberation analyses of the HydroFloat™ testwork feed, concentrate and tailings streams by size can be used to determine the distribution and recovery of valuable minerals by exposure surface area. This will indicate the class of mineral particles which have a higher probability to be recovered to concentrate.

Laboratory flotation testing on the HydroFloat™ concentrate at various regrind sizes (P_{80}) can provide key circuit design information such as target grind size, concentrate grade, tailings grade and mass recovery. This information feeds into the flowsheet development and influences where the HydroFloat™ concentrate and tailings products will be directed into the new or existing circuit.

The HydroFloat™ concentrate contains limited fine, comprised predominantly of gangue minerals which can be harder than the plant feed. There are limited HydroFloat™ concentrate regrind installations available for benchmarking in the development of new operations with the reliance of testwork for specific energy determination. To quantify the specific energy requirement to achieve a target grind size there are a number of vendor and non-vendor tests are available including:

- Levin standard test (Non-Vendor)
- Levin modified test with 19mm media (Non-Vendor)
- Bond test (Non-Vendor)
- Metso:Outotec Jar Mill test (Vendor)
- Nippon Eirich Tower mill (Vendor)

The authors have been involved in several projects where non-vendor testing was conducted in parallel to vendor testing to reduce risk and reliance on the vendor tests for material with limited historical benchmarking.

Hatch has worked on coarse particle flotation circuit design and installation through PFS, FS and Detailed Design Engineering phases for an Australian Cu-Au operation who wanted to address flotation recovery losses as part of a plant expansion. Early study phases analysed flotation circuit survey data and mass balance results showed that on average 45% of copper loss to tails was coarser than 106 µm, and of these particles, the majority displayed low surface exposure of copper sulphides.

Technology trade-off analysis was conducted for the selection coarse particle flotation flowsheets for circuit modelling. Several options of pre-classification were identified for further analysis with a common downstream flowsheet selected that included coarse particle flotation, dewatering cyclones and concentrate regrind followed by a cleaner Jameson cell. The dedicated HydroFloat concentrate treatment equipment was selected to maximise liberation and minimise the load on the existing cleaning circuit.

The coarse particle flotation concentrate is reground to 38 µm in a Vertimill™ operating in closed circuit with a cluster of regrind cyclones. The inclusion of the concentrate regrind and cleaner Jameson Cell in the flow sheet allowed a high-grade low mass concentrate stream to be directed to the cleaner circuit and the lower grade Jameson tailings stream to be returned to the head of rougher circuit.

Several coarse particle flotation circuit mass balances were produced during this project for equipment design and capacity checks utilising Limn to model Cu, Au and gangue by size, mass and volume flows and cell performance, as shown in FIG 7. Circuit recovery and concentrate grade will be a function of the circuit configuration and performance including the pre-classification recovery-by-size, ore floatability, HydroFloat™ cell operating parameters, concentrate mass, regrind mill size and Jameson Cell operating parameters.

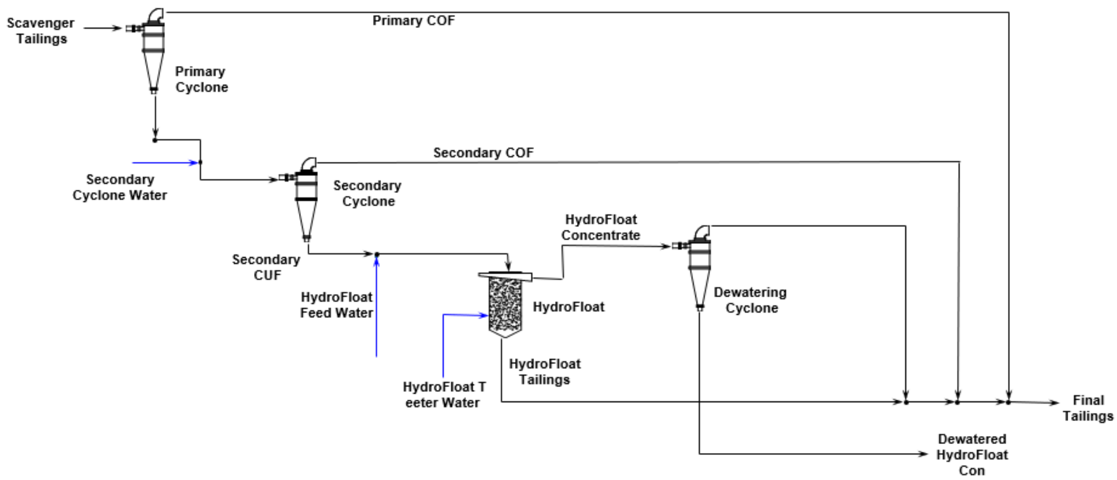

FIG 7 – Coarse Particle Flotation Limn Flowsheet

Preliminary simulations of the proposed flowsheet configurations were conducted using the plant flotation model with the additional of the coarse particle flotation circuit (Table 1).

- **Simulation 1**: **Single Stage Cyclones**. A single stage cyclone pre-classification circuit ahead of the HydroFloat™. The single cyclone stage had the lowest classification efficiency with larger mass flows require to maximise the recovery of coarse material to coarse particle flotation.
- **Simulation 2**: **Two Stage Cyclones**. A two-stage cyclone pre-classification circuit ahead of the HydroFloat™. The dual stage has an improved classification efficiency relative to a single cyclone stage.
- **Simulation 3**: **Crossflow™ Classifiers**. A pre-classification circuit containing a cyclone stage followed by Crossflow™ classifiers ahead of the HydroFloat™. The Crossflow™ classifier

classification circuit provided the highest classification efficiency of the classification options. However, this option has high process water consumption (+50%) relative to the other options.

A preliminary trade-off study was conducted to further reduce the number of options, with the single and dual stage cyclone pre-classification options chosen for further simulation and preliminary engineering. Additional simulations were conducted to identify the most promising circuit flowsheets, equipment sizes and circuit configurations to allow coarse, lean composite Cu & Au sulphide bearing mineral particles to be scavenged and recovered.

Table 1 – Simulation results of the coarse particle flotation circuit

Parameter	**Base Case**	**Simulation 1**	**Simulation 2**
Rougher-scavenger tails, t/h	2392	2518	2497
Dewatered coarse particle flotation concentrate, t/h	-	127	106
Dewatered coarse particle flotation concentrate Cu grade, %	-	0.46	0.5
Dewatered coarse particle flotation concentrate Au grade, g/t	-	0.97	1.05
Cu grade in final tail, %	0.079	0.65	0.66
Au grade in final tails, g/t	0.15	0.12	0.12
Cu flotation recovery, %	77.6	81.7	81.3
Au flotation recovery, %	70.0	75.8	75.2
Change in Cu recovery, %(Delta)		**+4.1**	**+3.7**
Change in Au recovery, %(Delta)		**+5.8**	**+5.2**

The dual cyclone option was identified as the option that provided the optimum balance between operability, maintainability, CAPEX and recovery. A dual stage cyclone classification was selected for the pre classification circuit to progress to feasibility and detailed engineering design. The upgraded flotation circuit with coarse particle flotation was modelled in JKSimFloat using inputs from the coarse particle flotation circuit Limn model. The JKSimFloat circuit flowsheet is shown in FIG 8.

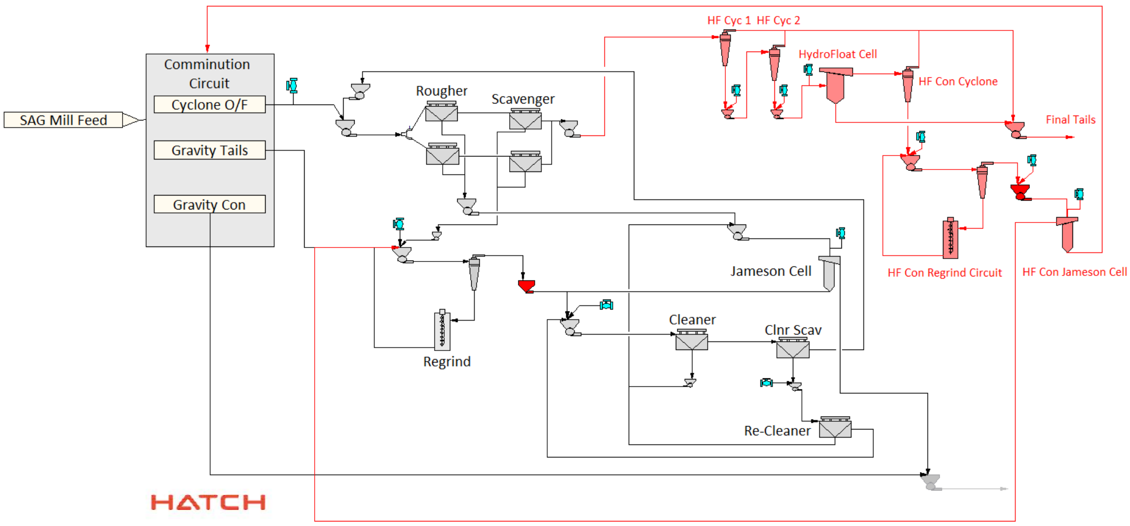

FIG 8 – JKSimFloat model for upgraded flotation circuit with Coarse Particle Flotation Circuit

With each of the pre coarse particle flotation classification circuits investigated, the imperfect classification resulted in a portion of the fine material reporting to coarse particle flotation feed. Fine particles reporting to the HydroFloat™ feed will be hydraulically carried to the concentrate by entrainment through the continuous overflow of teeter water over the lip of the concentrate launder. The circuit included deslime/dewatering cyclones ahead of the regrind circuit to remove the low-grade fines. The majority of the fine material reporting to the concentrate results in HydroFloat™ tailings comprising mostly of coarse particles, with challenging material properties including high abrasiveness and poor particle suspension. To aid the slurry material properties the flowsheet combined the fines containing dewatering cyclone overflow and the two pre-classification cyclone overflow streams with the HydroFloat™ tails in the launder prior to the tailings hopper.

Material properties of the HydroFloat™ tailings and high process water demand of the coarse particle flotation circuit in combination with upstream and downstream equipment availabilities were also a consideration in the inclusion of bypasses in the overall flowsheet design. The flowsheet was designed with cyclone overflow recycles in the pre-classification circuit to enable the cyclone feed pumps to continue to run with minimal additional process water during start-up, shut-down or if the feed to the coarse particle flotation circuit is bypassed. A recycle of the coarse particle flotation tailings was included in the flowsheet to enable to coarse particle flotation circuit to be recycled for a short time if there was downstream limitations. The coarse particle flotation circuit tailings reported to the existing tailings thickener to maximise the recovery of process water.

ENERGY-EFFICIENT AND SMALL FOOTPRINT FLOTATION CELLS

Flotation optimisation has traditionally been focused on grade and recovery performance improvements. However, with the growing need for energy efficiency and the dramatic increase in flotation cell size in recent years it is worth considering how well energy is utilised within flotation cells. In conventional mechanical flotation cells a certain amount of energy is required to meet the basic requirements for flotation (air dispersion, solids suspension and particle-bubble collision and attachment). Tabosa et al. (2016) have shown that flotation rate in the collection zone and the fraction of the cell with higher turbulence increases as more of the power drawn by the impeller is dissipated as shear in the impeller-stator region. They have shown that recovery improved for conditions that increase the volume of the highly turbulent zone and thus achieve high local energy dissipation near the impeller. This ensures more efficient use of the energy imparted to the impeller and should promote higher collision rates. However, improvements in the collection zone may not translate to an increase in overall recovery unless improvements to the froth phase are implemented to minimise the detrimental effect of turbulence on the froth zone recovery. Ideally, bubble-particle collision/attachment and the froth separation could be considerably optimized if carried out in separate units.

New mechanical flotation cell technologies such as these supplied by Eriez's StackCell® (FIG 9) and Woodgrove (SFR – Staged Flotation Reactor and DFR – Direct Flotation Reactor, FIG 10) decouples the particle-bubble collection zone within the cell from the froth phase separation process. These alternatives have been developed with the goal of providing more efficient flotation using separate chambers for particle-bubble collision and for froth separation. These devices build on the concept of focused energy input to enhance fine particle and relatively coarse particle (DFR) recovery as well as improving flotation kinetics. Similarly to high-intensity pneumatic flotation cells (e.g., Jameson, PneuFloat and Imhoflot G-cells), these technologies provide a high intensity contained reactor zone where fine bubbles are generated and intensely mixed with feed pulp before discharging into a quiescent separation chamber. The difference, however, is that the high intensity energy in these devices is generated by moving parts (i.e., impeller) rather than by injection of air under high-pressure or air induced by vacuum in the aerator of high-intensity pneumatic flotation cells (Hassanzadeh et al., 2022.)

The Staged Flotation Reactor (SFR) is a flotation cell comprising three separate stages: particle collection, bubble disengagement and froth recovery (FIG 10). By decoupling the three processes, the SFR aims to optimise each of the three processes separately. The rotor in the particle collection chamber (tank) is designed to provide localised high energy input through a high shear impeller zone leading to high particle-bubble collision/attachment (i.e., high collection efficiency). The second tank purpose is to deaerate the slurry (bubble disengagement) and rapid recovery froth to the lauder minimising froth drop back. The third tank or froth recovery unit uses wash water and high solids flux. It is worth noting that the principle of operation of the Woodgrove Technologies Staged Flotation Reactor (SFR) is very similar to Eriez StackCell®s (see FIG 9). Some significant installations of SFR units in copper concentrators are BHP-Billiton's Spence and Tech Resources Limited 's Quebrada Blanca 2 in Chile, which combines FLSmidth 600 m^3 nextStep cells in rougher duty with SFR(s) in cleaner-duty. The development of the Staged Flotation Reactor was followed by the Direct Flotation Reactor (DFR) - a flotation cell which operates without the froth phase. The complete DFR unit is pressurized and has low footprint due to the lack of the froth phase. According to Woodgrove Technologies the main advantages of the SFR and DFR cells include reduced power/air consumption, reduced footprint, reduced installation and infrastructure costs (e.g., DFR units can be installed on the same level) (Moore, 2021). Unfortunately, at the time this paper is written, technical information on the metallurgical performance of Woodgrove Technologies cells or industrial flotation circuits comprising only SFR and/or DFR units in public domain is scant or almost inexistent. This certainly affects the confidence of engineering and mining companies to embrace this type of cells in large throughput concentrators (e.g., rougher duty).

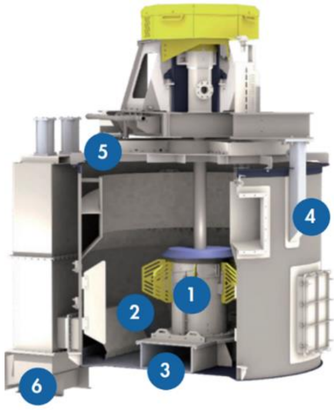

FIG 9 – Eriez StackCell®: 1. collection chamber, 2. separation chamber, 3. feed inlet, 4. froth, 5. wash water system, 6. tailings discharge (Eriez, 2022).

FIG 10 – Woodgrove Staged Flotation Reactor (left) and Direct Flotation Reactors (right) (Nelson and Lelinski, 2019 and Woodgrove Technologies, 2022)

The authors of this paper have been evaluating the metallurgical performance of these alternative flotation technologies in greenfield and brownfield optimisation and expansion at concept, pre-feasibility, and feasibility level projects. In brownfield expansion projects, for example, available footprint is often an issue and alternative solutions to installing conventional mechanical flotation cells need to be evaluated to deliver the equivalent capacity and eliminate the need for constructing additional building for new flotation equipment.

Furthermore, overall unit size can be reduced while maintaining the same (or higher) capacity and metallurgical performance. The implications of this step-change in technology are numerous and include a significant reduction in energy consumption (> 40%) as well as reductions in plant height, footprint and foundation loads of greater than fifty percent.

Seaman et al. (2021), for example, have looked at alternatives to overcome rougher residence time and footprint limitations in the rougher flotation bank at Red Chris Mine, Canada. Additional 600 m^3 of rougher capacity was required and they considered SFR/DFR and StackCell technologies. Jameson cells were also considered for this duty. They demonstrated that Eriez StackCell®s have superior kinetic performance compared to conventional mechanical tank cells, with flotation rates for copper and gold bearing minerals being at least four times faster compared to the plant cells. They have also shown that the required rougher volume increase of 600 m³ to overcome rougher residence time limitations can be fulfilled by 25% of this volume using two 75 m³ StackCell®s with Hatch completing PFS engineering to fit these cells inside the existing process building.

The authors of this paper have also conducted a trade-off study between the Staged Flotation Reactor (SFR) and Direct Flotation Reactor (DFR) for the cleaner scalper of a North American copper-gold concentrator as part of the flotation expansion project. The flowsheet investigated for the scope of this trade-off is presented in FIG 11, which presents a clear depiction of the new unit operation within the existing processing circuit. The SFR or DFR were tested in cleaner-scalper duty taking primary high-grade regrind cyclone overflow. The regrind cyclone overflow consists of freshly reground rougher concentrate. The SFR or DFR concentrate is sent directly to final concentrate while the tailings will either feed the existing 1st cleaners or bypass directly into the 1st cleaner tailings.

Pilot-scale testwork was performed by taking a bleed from the regrind cyclone overflow under 3-pass and 4-pass scenarios to evaluate the use of 3 or 4 SFR or DFR units in series. However, the pilot-scale testwork for the SFR and DFR were conducted three years apart; therefore, the ore parameters feeding the mill during these two campaigns were subject to the ore conditions from the mine. The SFR campaign processed lower copper grade than the DFR campaigns, but both campaigns had similar gold feed grade.

FIG 12 shows the best pilot-scale testing results of the SFR and DFR units (with 3 and 4 passes). It can be clearly seen that the SFR had a superior metallurgical performance than the DFR units for Au and Cu recovery and enrichment ratio. For example, at 8% mass pull the SFR and DFR Cu recoveries sit around 90 % and 65%, respectively. Regarding the SFR and DRF Cu versus Au recoveries, FIG 12 clearly shows that most of the data points of the SFR sit above 80% Cu and 50% Au recovery. In contrast, most of the data points for the DFR testing sit above 60% Cu and 40% Au recovery. And finally, regarding Cu and Au enrichment ratio (or selectivity) versus mass pull the SFR units again outclassed the DFR units with enrichment ratios above 12 and 8 for Cu and Au versus above 6 for Cu and 4 for Au for the SFR units.

The SFR processed feed with a much higher pyrite to chalcopyrite ratio than the DFR. Both SFR and DFR banks (3 units in series) can be installed within the existing processing plant constraints. The SFR bank and the required auxiliaries take an area of approximately 126 m², whereas the DFR bank only take about 68 m² area. Besides the smaller foundation area that DFR requires, this option also takes less vertical space since all the DFR cells are on the same level and no equipment needs to be elevated. Capital costs of the DFR cells were also around 8% lower than the SFR cells, with OPEX of the DFR being slightly lower than the SFR.

Although the DFR requires a smaller footprint and no elevation, the SFR cell outperformed the DFR during the pilot-scale testing in cleaner-scavenger duty. In addition, there are currently more industrial installations of SFR than DFR processing similar Cu/Au ore types in cleaner-scalper duty. Therefore, installing three SFR units to increase cleaner circuit capacity and also to improve the flotation circuit metallurgical performance was the preferable option.

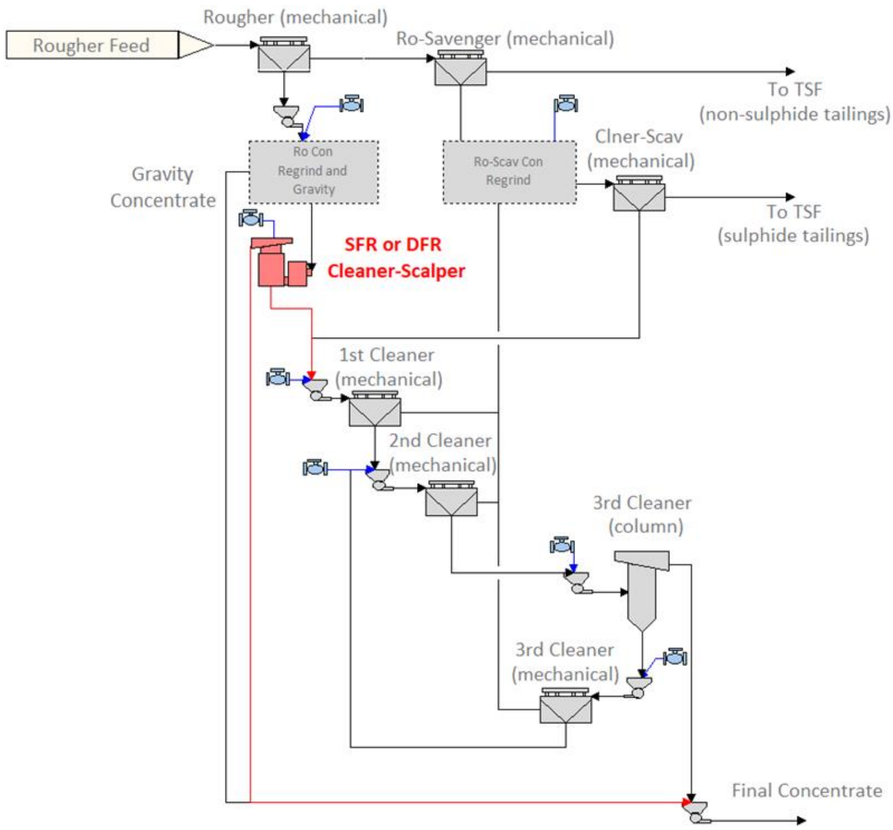

FIG 11 – Simplified Flotation Flowsheet of a Cu/Au operation

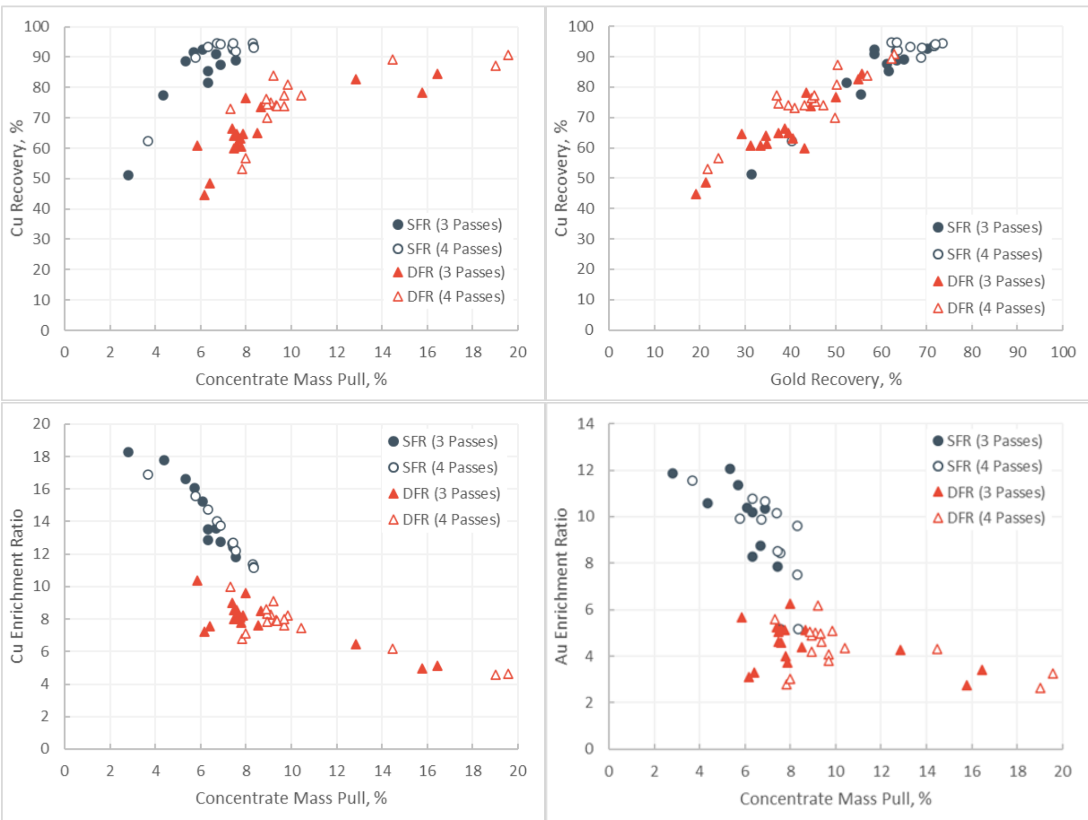

FIG 12 – SFR and DFR pilot metallurgical performance in a Cu/Au operation

CONCLUSION

The mining industry faces multiple challenges such as processing low-grade, mineralogically complex ore bodies, reductions in energy consumption and carbon emissions, water scarcity /quality, environmental, social and governance issues etc. At the same time, the demand for metals like copper, iron, cobalt, lithium and nickel is projected to reach its peak by 2050 (Watari et al., 2020).

Traditionally, flotation circuits design, equipment sizing and selection are performed based on laboratory and/or plant-scale test work (e.g., kinetics and locked-cycle tests) complemented by detailed mineral/liberation characterisation and personal experience (benchmarking data). Software packages such JKSimFloat, SysCAD, HSC Chemistry, METSIM and Limn are largely used to perform mass balance, in model development and simulation. However, there is a strong need to incorporate financial analysis modules (revenue maximisation or cost minimization) on the flotation software packages.

The future of flotation circuit design will incorporate different cell types such as mechanical with or without froth wash water, pneumatic (e.g., Jameson, Columns) and hybrid cells (e.g., Reflux Flotation Cell, HydroFloat, NovaCell) in brownfield and greenfield projects in conventional and, more importantly, in non-conventional applications such as coarse gangue removal (pre-concentration) prior to flotation using flotation devices like the Eriez HydroFloat™ or Jord International's NovaCell™. In addition, in large throughput base and precious metals circuits, flotation machines such as Glencore Technology Jameson cells, Eriez StackCell®s and Woodgrove Direct/Stage flotation reactors will likely have to be scaled-up to process high solids flow rates (e.g., First Quantum Cu/Mo Panama, Anglo American Cu/Mo Los Bronces operations) if operated in rougher duty. In precious and base metals coarsening the feed to flotation to a P_{80} in excess to 200 µm is likely to become more prevalent to minimise energy consumption, carbon emissions, and to reduce costs and/or risks of downstream processes like thickening, filtration, tailings management, etc.

Flotation will continue to be a powerful and versatile concentration method in the foreseen future. And, flotation circuit design, equipment selection and sizing will keep adapting to tackle the current and future mining challenges. This will require engineering companies working closely with mining companies, flotation equipment manufacturers, reagent suppliers, Universities and Technology centres.

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