DRIVING STAGEWISE DEVELOPMENT OF GOLD PROJECTS WITH THE JAMESON CONCENTRATOR AND ALBION PROCESS™

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ABSTRACT

Extending the life of a depleted gold mine can be as simple as treating and recovering gold from neighbouring sulphide deposits and tailings. However, gold is often finely disseminated in iron sulphides within the mineral matrix, making dissolution via direct cyanidation ineffective. Processing this refractory ore yields poor gold recovery, therefore pre-treatment is required to concentrate and oxidise these iron sulphide minerals prior to cyanidation. This includes flotation to concentrate the sulphide mineral fraction, followed by sulphide oxidation and then gold dissolution and recovery. Glencore Technology works closely with resource development organisations to evaluate a stagewise implementation of technologies to treat their sulphide ore reserves. This involvement begins early with collection of laboratory data to support the design and installation of a Jameson Concentrator™, followed by ultrafine grinding with the IsaMill™, and finally construction of an Albion Process™ plant utilising our OxiLeach™ Reactors (OLR). The Albion Process™ combines ultrafine grinding and oxidative leaching at atmospheric pressure, a proven process for sulphide mineral oxidation. Stagewise plant implementation allows for staggering equipment design and delivery schedules to expedite the path to establishing revenue. This is achieved by aiming for production of a saleable grade of flotation concentrate in the first stage of plant operation, with on-site dore production occurring after commissioning of subsequent plant stages. On-site sulphide oxidation allows the processing of a lower grade, higher recovery concentrate without the transport costs and penalties associated with concentrate trading terms. The design and delivery of these downstream stages can occur in parallel to construction of the Jameson Concentrator™ flotation circuit. This approach inherently carries higher risks and rewards. This paper reviews the application of GT technologies in the context of stagewise implementation, including compliance with environmental, social and governance (ESG) criteria and impacts on project execution.

Keywords: Gold, Jameson, IsaMill, Albion, Testwork, Staged Implementation, Production

1. Introduction

As reserves of easily recoverable oxide gold ores are depleted, operations are increasingly looking to extend the life of mine by treating and recovering gold hosted in neighbouring sulphide deposits and tailings. In these ore bodies, gold is often finely disseminated within the sulphide matrix, making it unamenable to direct cyanidation and resulting in poor gold recovery. For such projects, the question exists as to how to best treat sulphide ores; a decision which is influenced by multiple factors including offtake opportunities, legislation and existing infrastructure. Whilst many sites have elected to generate a saleable con, higher transport costs and penalties associated with concentrate trading terms are often incurred, and in some countries there are restrictions on the sale of intermediate products, leaving operations with no choice but to generate a final product.

Generating a final product from sulphide ores requires pre-treatment to render the finely disseminated gold amenable to cyanide leaching. This includes a flotation stage to generate a higher-grade concentrate, followed by sulphide oxidation. Stagewise plant implementation allows for a progressive approach to the design, installation, and commissioning of these stages of production, resulting in staggered delivery schedules, earlier product generation and an expedited path to establishing revenue. The first stage of plant operation aims to produce a saleable grade of flotation concentrate to provide a source of revenue until on-site doré (final product) production is achieved after subsequent plant stages are commissioned.

Glencore Technology (GT) works closely with resource development organisations to create bespoke flowsheet solutions to achieve maximum economic and environmental benefits. GT is the proprietor of several specialised technologies suited to stagewise implementation and has extensive expertise evaluating their amenability to treat unique refractory ores. This paper reviews the application of GT technologies in the context of stagewise implementation, including compliance with environmental, social and governance (ESG) criteria and impacts on project execution.

2. Stagewise Implementation – from Ore to Doré

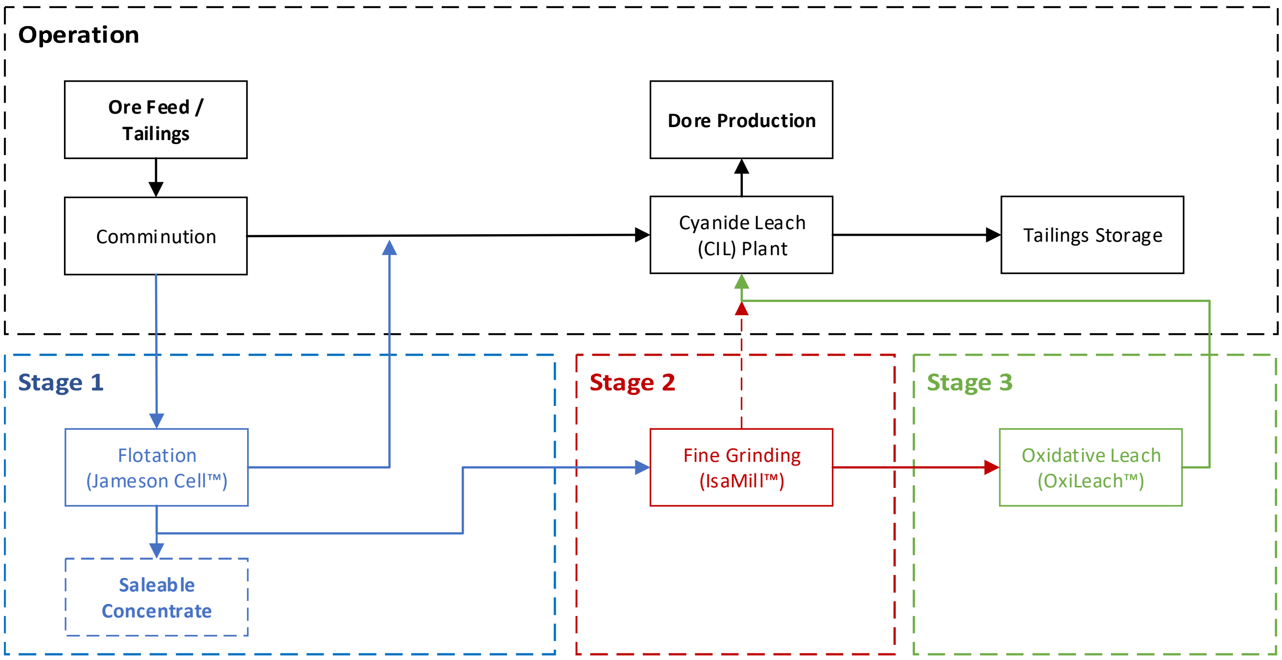
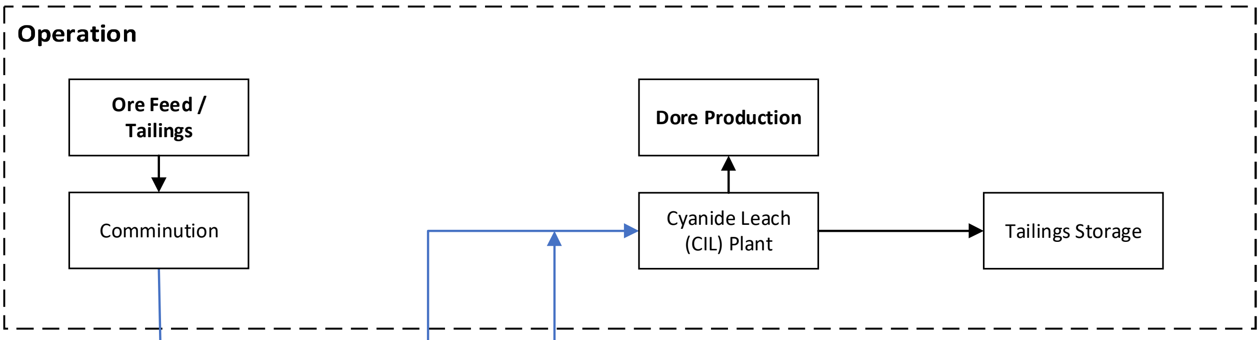


Figure 1: Stagewise Implementation Using GT Technologies

GT's approach to treating refractory gold ores includes three stages (**Error! Reference source not found.**). The first stage is the building and commissioning of a flotation circuit to produce a saleable concentrate. Stage 2 adds a fine grinding mill to achieve better mineral liberation and improved recoveries. Stage 3 involves the building and commissioning of an oxidative treatment plant to enhance downstream cyanide leaching recoveries. A stagewise approach to implementation allows for expedited revenue generation upfront using well understood mineral processing technology while the downstream plant is fully tested, designed and commissioned.

This section describes GT technologies and processes and their role in stagewise implementation, initially leveraging a saleable concentrate to create capital to build a full leach plant for the production of dore on site.

2.1 Stage 1: Flotation and the Jameson Concentrator



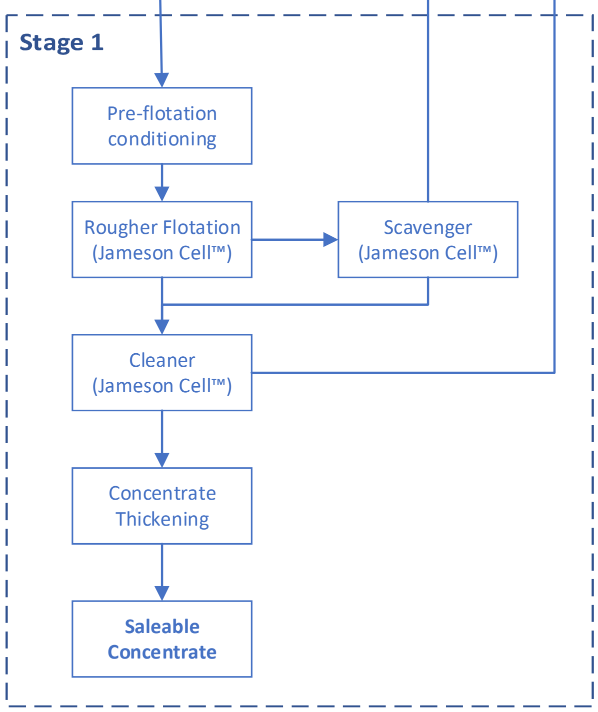


Figure 2: Stage 1 Jameson Concentrator

Commissioning of a flotation circuit is the first step in stagewise implementation to extend the life of a depleting asset. However, increasingly complex ore bodies and stricter specifications pertaining to penalty elements require more efficient technologies to produce saleable concentrates.

The Jameson Cell™ is a self-aspirating, high intensity flotation cell that combines pulp and air in a vertical downcomer. The pulp is introduced via a slurry orfice lens, resulting in a high velocity which generates fine bubbles and maximises collisions with particles, enhancing the collection of mineral particles and generating a dense foam. The pulp is then discharged into a separation tank, allowing the foam to rise to the top as a froth layer for collection. The Jameson Cell™ also incorporates froth washing to minimise entrainment of gangue materials, increasing concentration grades to meet specification.

The Jameson Cell™ contains no moving parts (e.g agitators, blowers, rotors or compressors) and boasts rapid collection kinetics. Its residence-time-independent design allows for a significantly smaller circuit footprint (up to 50% reduction compared to conventional flotation cells) (Example 1).

Example 1: ESG benefits of Jameson Cell Concentrator

GT was commissioned to design of a 7 million tonnes-per-annum lead-zinc concentrator for a mineralogically complex ore project. Conventional flotation would have required 63 tank cells. Replacement with Jameson Cells lowered the cell requirement to 19 and reduced the flotation circuit footprint by 50%. Additionally, reduced earthworks, concrete, and structural steel combined with only using 30-60% of the energy of a conventional flotation circuit resulted in significant CAPEX and OPEX savings.

Jameson Cell™ technology was originally installed at the head of conventional cleaning circuits to improve cleaning capacity, minimise deportment of deleterious elements, and generate a high grade final concentrate. There are over 500 Jameson Cell™ installations across coal, precious and base metals, potash, and oil sands, demonstrating its reliability for new circuits and upgrading existing ones. The advantages Jameson Cells™ have over conventional flotation units has resulted in the introduction of a full Jameson Concentrator™ layout in several operations. The Jameson Concentrator™ is easily constructed by an EPCM to go live quickly, allowing quick turn arounds and commencing cash flow as early as possible. Implementing a Jameson Concentrator™ circuit rapidly produces a high-grade saleable concentrate and raises capital to implement Stages 2 and 3.

The flexibility of the Jameson Cell™ underpins efficient stagewise implementation, due to its ability to operate at numerous points along the grade recovery curve. When an operation progresses from generating a saleable concentrate to producing dore on site, the Jameson flotation circuit can be reconfigured to maximise recovery. The operation of the Jameson cells makes it possible to change the function of the plant to meet this future stage of processing where a bulk concentrate of lower grade is required, either by operating at a different point on the grade recovery curve or configuration of the circuit. Cleaners are able to be switched to treat the scavenger concentrate only or could be utilised at the head of the circuit to achieve a higher overall plant throughput.

Figure 2 shows a typical concentrator consisting of a rougher, scavenger and a cleaner to produce a final saleable concentrate grade. This configuration is to ensure the ability to produce a high grade / saleable concetrate. If mineralogy and liberation issues exist further regrinding may be required to assist in achieving the desired results. In certain applications and during treatment of transition material it may be possible to produce a final concentrate grade at an acceptable recovery from a single Jameson Cell™ or a simple rougher scavenger Jameson Cell™ circuit.

2.2 Stage 2: Introduction of Fine Grinding

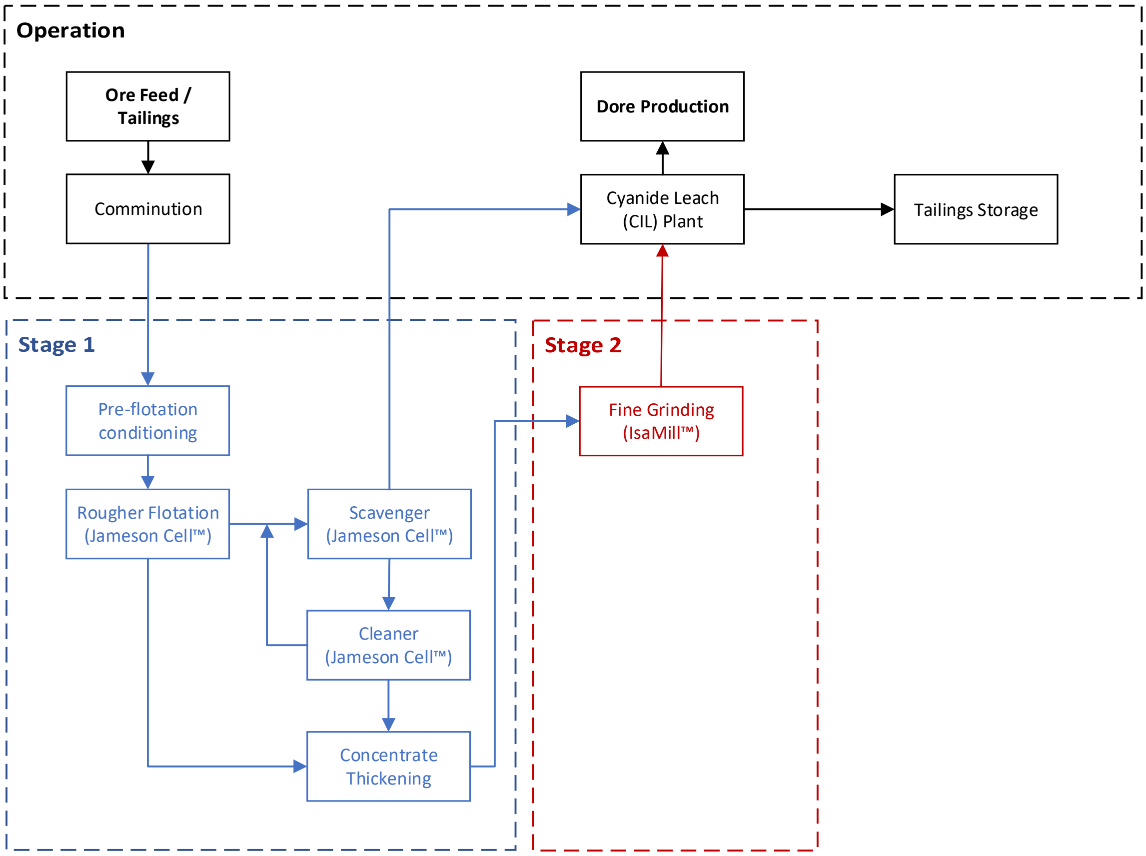


Figure 3: Stage 2 Ultrafine Grinding and Jameson Concentrator Modifications

As the operation progresses from selling concentrate to producing all of the gold as dore on site then the introduciton of a fine grinding stage may provide an ecomonic interim solution (Figure 3). For some projects, fine grinding alone may result in sufficient liberation of the gold for recovery in traditional downstream processes (Example 2). Many conventional mills are inefficient in fine grinding duties due to prolonged milling times, resulting in low throughputs and high power consumption. Ultra Fine Grinding (UFG) mills like the IsaMill™ overcome the limitations of conventional mills by using rotating stirrers within a stationary mill shell, offering an energy efficient means of achieving ultrafine grind sizes.These sizes achieve better liberation of gold encapsulated within the sulphide matrix.

The IsaMill™ is a well-established, highly efficient fine grinding mill capable of achieving the tight size distribution required to enhance the rate of downstream chemical reactions. This key parameter is tracked in the testwork by measuring the coarse size index (CSI) which is a ratio of the p98 to p80. This is achieved by a plug-flow design that incorporates multiple grinding chambers.

Example 2: Ultrafine Grinding (UFG) using the IsaMill as a replacement for roasting – environmental and economic benefits

A refractory gold processing operation was investigating opportunities to eliminate their existing roaster. Pressure oxidation, biological oxidation and ultrafine grinding were investigated as potential alternative processes. Economic analysis indicated that UFG had the highest Net Present Value return of the alternative process options. The inclusion of an IsaMill™ for UFG of the refractory gold concentrate to 10µm prior to cyanidation resulted in an increase in recovery from 75% to 92%. The replacement of roasting with UFG via IsaMill™ also eliminated harmful air emissions whilst maintaining production rates.

As the central shaft rotates, the grinding discs and grinding media are agitated, causing the media to centrifuge out along the disc face towards the shell liner. The media is then redirected back towards the mill shaft. Slurry fed to the mill must pass through each grinding chamber before exiting and is unable to short circuit the mill. The slurry discharges through a product seperator with a closer spacing between the final and rotor discs to centrifuge coarser particles toward the shell, at which point the rotor directs the material back into the grinding zones (Figure 4).

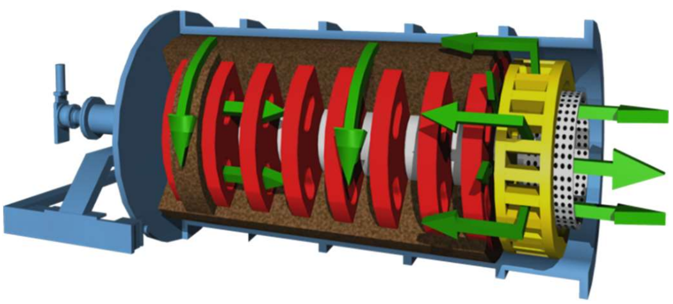


Figure 4: Slurry and media flow through the IsaMill™

The design of the IsaMill allows for efficient particle flow and grinding, retention of grinding media, and minimises the potential for particles to short circuit. This achieves the tight size distribution necessary for efficient oxidation and high gold recoveries in downstream cyanide leaching. Additionally, the horizontal design of the IsaMill™ allows for a single floor design and offers greater power intensity compared to alternative fine grinding mill options. GT has accredited laboratories perform designated IsaMill™ testwork on every client's sample to generate an IsaMill™ signature plot for specific grind energy. Tests are performed in a continuous mode to replicate full-scale performance, resulting in a 1:1 direct scale up from testwork to full-scale.

2.3 Stage 3: Albion Process and downstream processes

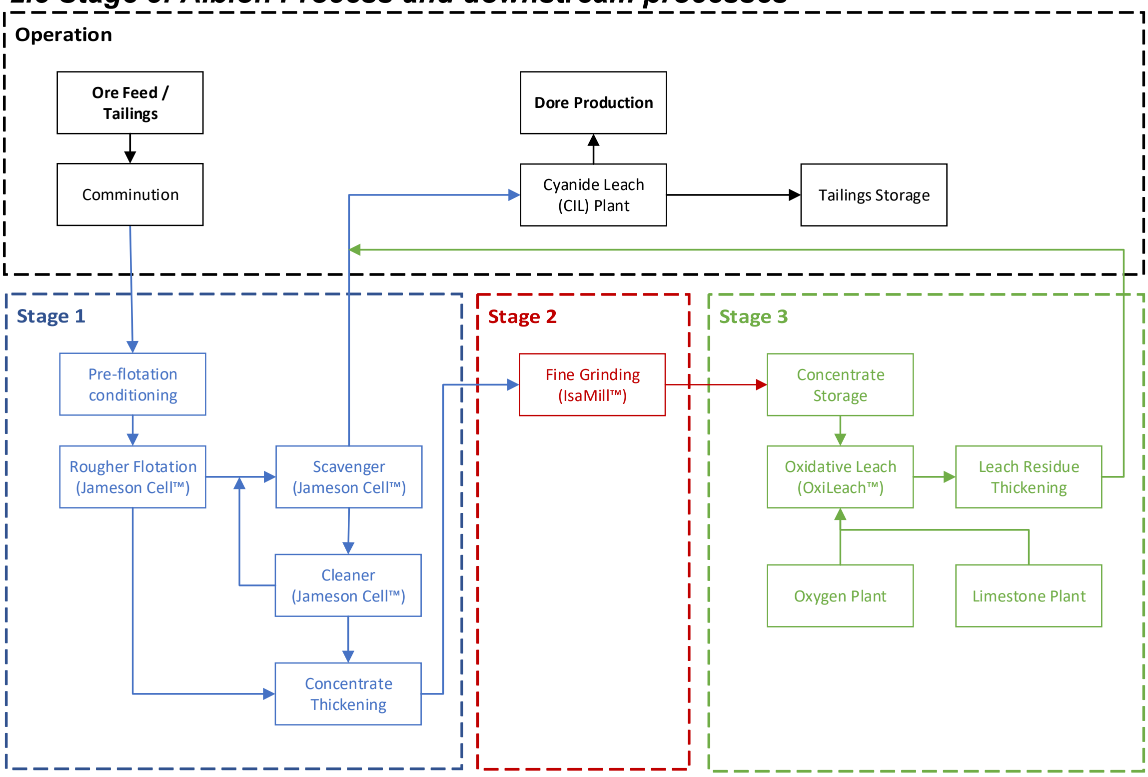


Figure 5: Stage 3 Albion Process full implementation

If the gold is extremely refractory and is not amenable to extraction after UFG alone, oxidative treatment may be required. The Albion Process is a globally patented technology developed by Glencore Technology in 1994. It consists of two stages: (i) ultrafine grinding in the IsaMill™ and (ii) oxidative leaching. Therfore the oxidative leaching step may be added after UFG in a project requiring stagewise implementation.

During the first stage, feed material undergoes UFG in an IsaMill™ to increase surface area and minimize potential passivation of the mineral surface during leaching. The high degree of residual strain within the crystal lattice coupled with increased surface area results in a high defect density within individual mineral grains and increased reactivity of minerals to oxidation. Therefore, less extreme conditions are required to effectively oxidise sulphide minerals, enabling leaching to occur at atmospheric pressure. This renders autoclaves unnecessary, leading to a safer, simpler, and more energy efficient plant.

During the second stage, oxidative leaching occurs in the OxiLeach™ Reactor System. This system utilises Glencore Technology's patented HyperSparge™ to inject oxygen at supersonic velocities. The high shear and increased particle contact achieved by the HyperSparge™ offers more efficient oxygen mass transfer in solution and maximises oxygen utilisation, thereby ensuring the process is not limited by oxygen mass diffusion. The hypersparge achieves oxygen utilisation of 80% or higher, compared to 50% as exhibited by other sparging systems (Voigt, Mallah and Hourn, 2017).

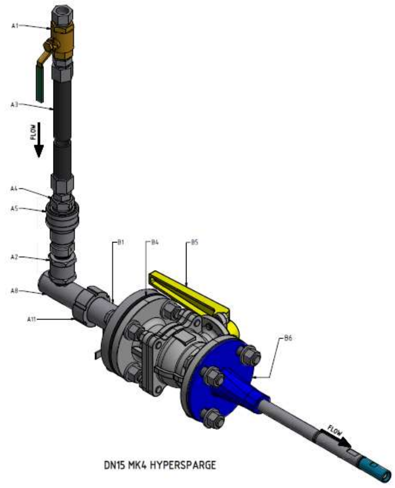


Figure 6: HyperSparger™ supersonic oxygen injection

Figure 7: OxiLeach™ Reactor

The leaching process occurs autothermally at atmospheric pressure (with the sulphide in feed targetted above 10%w/w) and, in the case of most gold bearing concentrates, under mildly acidic condidtions (approximately pH 5.5). Paradoxically, despite the term 'leaching', precious metals remain within the solid residue to be subjected to cyanidation or an equivalent gold extraction process while the liquour reports to treatment/tailings.

The Albion Process™ has been commercialised for both precious and base metals, with seven plants constructed and reported on extensively (Hourn & Turner, 2010; Hourn & Turner, 2012; Voigt, Hourn, & Mallah, 2016; Senshenko, Aksenoz, Vasiliev, & Seredkin, 2016). Compared to other oxidative leach processes, it is low cost, technically straightforward, effective, and safe. It eliminates the need for a large technical workforce, and due to its simple layout and atmospheric conditions, it avoids the myriad safety and process issues associated with other approaches. The Albion Process™ has also been shown to have up to one third lower operating costs compared to other oxidative leaching processes in part due to lower consumption of limestone and oxygen (24% less), water (58% less) and power (50% less) compared to traditional oxidation methods (McNeice, Marzoughi, Kim, & Ghahreman, 2021; Aylmore, 2012).

Example 3: Effectiveness and ESG benefits of the Albion Process ™ for treating refractory gold ores

The Ararat processing plant owned by GeoPro Mining (GPM) in Armenia is Glencore Technology's flagship gold processing operation. This plant was commissioned in January 2014 and produces 120,000 oz of gold per annum. The Albion process plant consists of a M3000 IsaMill™ and nine OxiLeach Leach Reactors. The introduction of the Albion plant to the Ararat flowsheet increased gold recoveries to 92%.

The plant is highly robust, able to operate with high variability in feed sulphide content and still achieve high gold recoveries above 95%. This is of particular importance due to the requirement of the plant to treat feed from seven different ore bodies, including three that are high in arsenic. During the process, arsenic is leached into the bulk solution. The addition of limestone (to control the pH to 5.5 within the range for optimal pyrite oxidation) allows for the co-precipitation of iron and arsenic, forming a stable ferroarsenate (predominantly scorodite). Subsequent testing of the Ararat tailings storage facility have confirmed the stability of the arsenic compounds.

4. Stagewise Implementation in the real world

The following section provides an example of a proposed stagewise implementation of GT technologies for an existing gold operation. The site has less than two years processing remaining for the current oxide ore body. The underlying sulphide deposit consists of pyrite hosted gold, with significant non-sulphide gangue present as silicates and carbonates. Due to the short time requirements for being able to process a sulphide ore, stagewise implementation will see the commissioning of a Jameson rougher-scavenger flotation circuit for the initial generation of a saleable concentrate.

4.1 Stage 1: Flotation (Jameson Concentrator)

Feed to the Jameson flotation circuit is characterised as follows:

Throughput	mtpa	1.0
	tph	125
P_{80}	µm	150
Au grade	g/t	1.9
S grade	%	0.8

The subsequent circuit to treat this feed will consist of one Jameson Rougher cell and one scavenger cell, equating to USD 12M capital expenditure and USD 0.9M operating expenditure annually.

The saleable concentrate produced by the Jameson flotation circuit will achieve gold recoveries of 85% gold at a mass pull of 6%, resulting in a gold concentrate grade of ~35 g/t. Using the current gold price of USD 65 per gram, selling this concentrate for 75% of payable contained value will provide USD 79 million per annum in revenue, in addition to the processing of remaining oxides, bringing additional revenue forward whilst remaining design, installation and commissioning is completed for Stages 2 and 3.

4.2 Stage 2: Ultrafine grinding (IsaMill™)

Single-stage ultrafine grinding will be achieved through the implementation of a M7,500 IsaMill™ with an installed motor power of 2,200 kW. Feed will be ground to 12 µm, with the available power offering flexibility to manage ore variability and future requirements. This stage equates to an annual operating expenditure of USD 2.5M and a capital expenditure of USD 13.5M. Whilst fine grinding alone provides a 20% uplift in gold recovery (from 20% to 39% after ultrafine grinding), unlike Example 2 earlier the economic benefits of a separate fine grinding stage prior to commissioning an oxidative leaching circuit are not recognised for this particular project, thus Stage 2 and Stage 3 will be implemented concurrently.

4.3 Stage 3: Oxidative Leaching (Albion Process™)

Upon commissioning of Stages 2 and 3, the flotation circuit settings will be configured to maximise recovery as opposed to grade. Flotation will achieve 95% gold recovery at a mass pull of 10%, yielding a feed to the Albion circuit as follows:

Throughput	tpa	100,000
	tph	12.5
P_{80}	µm	12
Au grade	g/t	18
S grade	%	9

The concentrate sulphur grade of 9% has been modelled and will allow for autothermal operation of the leaching circuit, negating the need for external heating. The leach residence time will be approximately 48 hours, during which 2.8 tonnes per hour of limestone and 1.5 tonnes per hour of oxygen will be dosed into the reactors. The capital cost of the Albion Process™ leaching circuit will be USD 22.2M, with an annual operating cost of USD 3.8M. After oxidative leaching approximately 96% of gold will be recoverable via cyanide leaching, equating to an uplift in gold recovery of 76% (absolute) attributed to the Albion Process™ and resulting in an annual revenue of USD 112M.

The total combined cost to facilitate the treatment of sulphide ore is USD 36.5, with an annual operating cost of USD 6.8M. With a stagewise approach to implementation costs are staggered over time, with capital cost consisting of stage 1 - 25%, stage 2 - 28% and stage 3 - 47% and the operating cost stage 1 - 12%, stage 2 - 36%and stage 3 - 56%. This highlights one of the key advantages of a staged approach to implementation, starting with lower capital and operating cost technologies to expedite revenue whilst concurrently staggering expenditure over time to improve cash flow and complete the subsequent stages to achieve high gold recoveries and a robust process for future production (Figure 6).

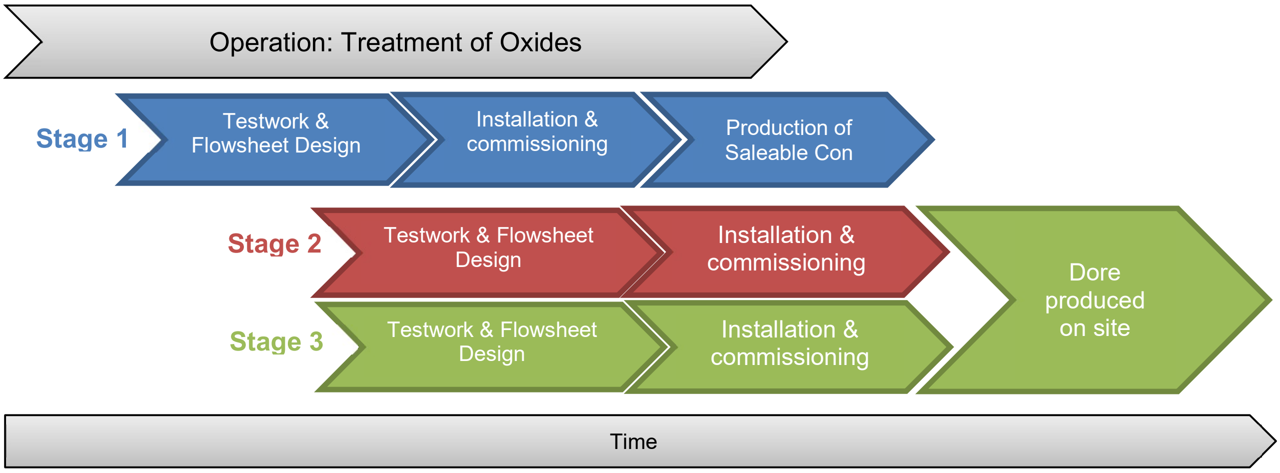


Figure 6: Staggered Implementation of Sulphide Treatment Stages

5. Conclusions

A stagewise approach to implementation allows eligible projects to extend the life of their operation by providing the opportunity to treat refractory sulphide materials. This approach ensures that revenue generation can initially commence through the production of a saleable concentrate while the downstream processes that will ultimately treat this concentrate onsite are refined in design and commissioned. The evaluation and comparison of differrent implementation stages should focus on comparing cost:revenue ratios or NPV rather than a sole focus on a designated recovery targets. This must then be supported by good financial modelling to ensure the most beneficial economic case is identified

GT provides several industry-proven technologies and processes that complement each other and facilitate a stagewise approach to implementation. All of these technologies are flexible and simple in their in operation, to compliment this approach to implementation. Applying this this to a real-world scenario for treating 1.0 mtpa of ore through a Jameson Concentrator to produce 100kt of concentrate through the Albion Process, the total cost of the project is USD 36.5, with an annual operating cost of USD 6.8M. A stagewise approach to implementation allows for costs to be staggered over time, with the capital cost consisting of stage 1 - 25%, stage 2 - 28%and stage 3 - 47% and the operating cost stage 1 - 12%, stage 2 - 36%and stage 3 - 56%. Thus for 25% of the capital spend and 12 % of the operating cost it is possible to start the implementation of the flotation stage and generate a saleable concentrate. This generates ~70% of the available gold revenue for the operation and sets up the project to complete the final stages to achieve high gold recoveries and production onsite with a robust plant for future production.