IMPLEMENTATION OF FINE GRINDING AND DUAL CIRCUIT CONCEPT AT SANTA ELENA MINE

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ABSTRACT

Santa Elena Mine, owned by First Majestic Silver Corp. (FMSC), is located 168 Km Northwest of Hermosillo, Capital city of Sonora State, Mexico; and formally commenced operation in 2011. The existing processing plant (commissioned in 2014) was originally designed as a dynamic leaching process with a nameplate capacity of 3,000 tonnes per day for a grind size P_{80} of 100 µm. FMSC and its metallurgical team, identified the opportunity to improve gold and silver recoveries through modifications to comminution processes that increase the exposure of valuables at particle sizes in the order of 15 to 30 µm. The implementation of the fine/ultrafine grinding circuit has demonstrated considerable benefits along with great challenges for the processing plant. This paper discusses aspects of the project in greater details such as the evolution from an idea to field commissioning, challegens encountered by the implementation of innovative concepts and technologies in an already stable operation, results of the Project first stage, progresses of the Project second stage, and future targets and considerations.

KEYWORDS

Fine/ultrafine grinding, Dual circuit concept, Gold and silver, Commissioning, Operation

INTRODUCTION

The Santa Elena Silver/Gold mine located in northern Mexico is approximately 150 km northeast of Hermosillo in Sonora State. The mine began operation in 2011 as an open pit, heap leach operation, and then transitioned to an underground mine in early 2014. In 2021, Ermitaño ores started to be mined and trucked to the existing Santa Elena processing facility. Currently, the Santa Elena processing plant is using a campaign method of ore processing for treating the Santa Elena and Ermitaño ores separately.

In early 2018, FMSC identified an opportunity for a substantial increase in metal recovery at the Santa Elena processing plant. The recovery increase is associated with processing of a finer feed through the leaching circuit. Modifications to the existing processes were considered necessary to achieve a finer leach feed. The concept of "Dual circuit" for Santa Elena was introduced, following two stages of project development and execution, namely Project first stage and Project second stage. The project consists of the implementation of a High Intensity Grinding stirred media mill ("HIGmill") and modifications required for debottlenecking of downstream processes.

HIGmills are vertical fluidized stirred mills that use high intensity, high speed rotor, and ceramic bead media to grind materials to fine and/or ultrafine particle sizes (Nielsen, 2016). These mills have been reported to offer significant energy efficiency benefits in fine/ultrafine grinding applications (Paz, 2019).

PROCESS OVERVIEW

The Santa Elena process plant was originally designed to treat a nominal 3,000 tonne per day (t/d) of ore, a mixture of freshly mined material and partially leached heap residue. Figure 1 shows the original process flowsheet, which comprises a three-stage crushing circuit, single-stage wet ball milling circuit, cyanide leaching, CCD (counter current decantation) thickeners, and horizontal vacuum belt filtration circuit. The ball mill circuit was designed to produce a product P_{80} of 100 µm to be sent to the leaching circuit. The ores are processed into gold-silver doré bars through a Merrill-Crowe process. The tailings produced from the processing facility are filtered and deposited as dry-stack tailings.

After one year and half of operation since the commencement, a trade-off analysis was performed to determine the optimum operating point to maximize metallurgical performance for improved overall mine economics. Subsequently, a decision was made to reduce the plant throughput from 3,000 t/d to an average of 2,500 t/d, resulting in finer grind size P_{80} and longer leaching residence time. As a result, higher metal recoveries and a more optimum and balanced operation were achieved.

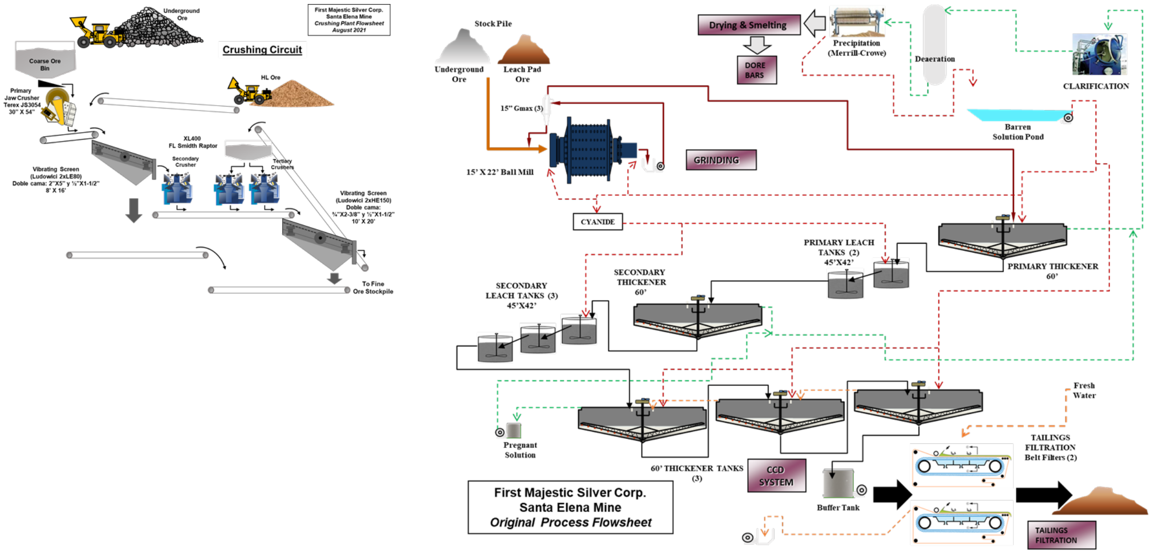

Figure 1 – Santa Elena original process flowsheet

OPPORTUNITY IDENTIFICATION

Metallurgical Testwork

Extensive mineralogy, comminution, and leaching testwork have been performed on both Santa Elena and Ermitaño ores. Most silver- and gold-bearing minerals were found attached or locked in light gangue, often in finely disseminated forms. Figure 2 compares the results of comminution testwork performed on Ermitaño ores and Santa Elena ores. It is evident that Ermitaño ores showed increasing ore competency, hardness and abrasiveness over the Santa Elena ores.

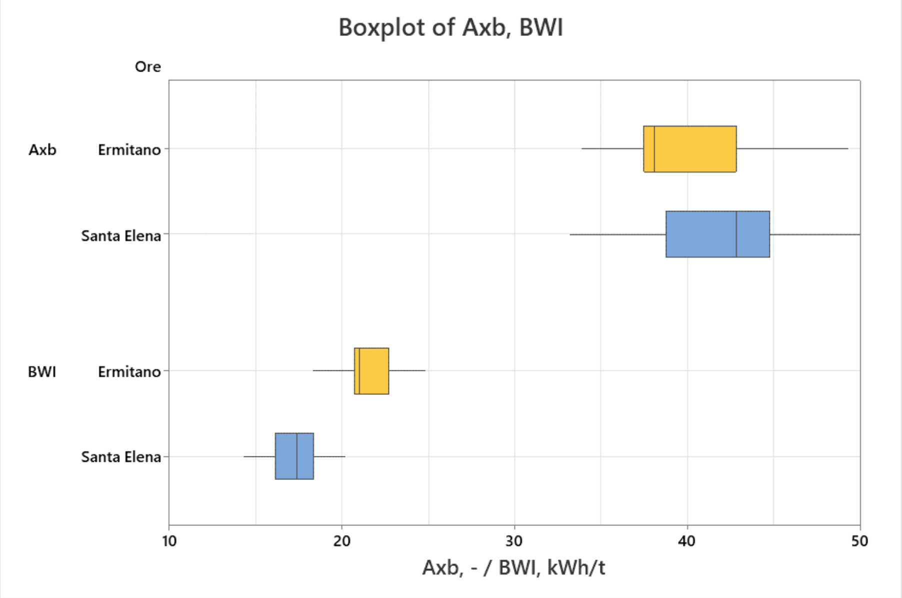

Figure 2 – Comminution test results for Santa Elena and Ermitaño ores

Figure 3 presents the gold and silver recoveries as a function of grind size P_{80}, suggesting that gold and silver extraction increased with the fineness of grind. Ermitaño ores were found to be more sensitive to grind size than the Santa Elena ores. Consequently, additional grinding power would be required to achieved the required grind size for enhanced metals extraction, particularly for the Ermitaño ores.

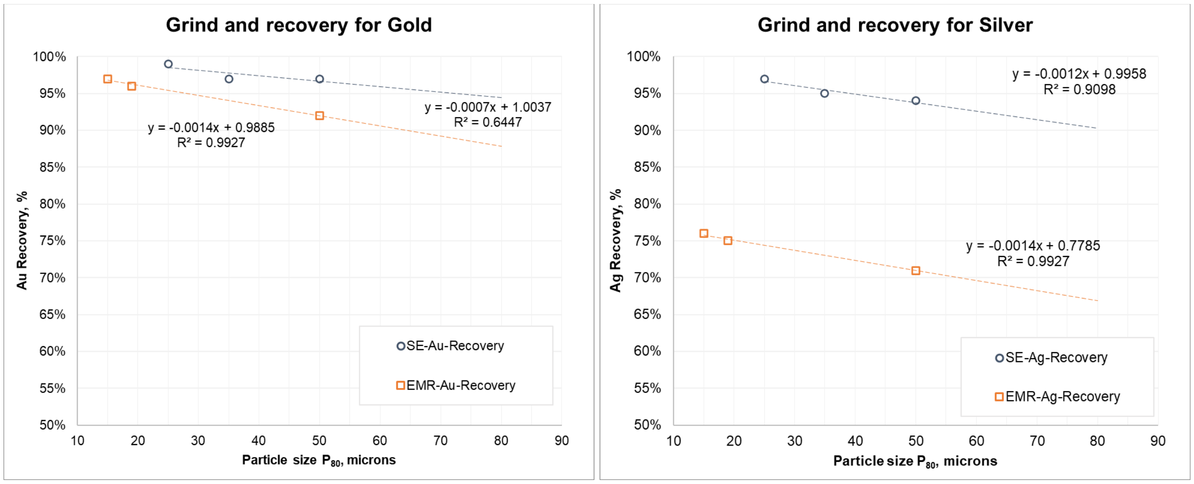

Figure 3 – Leaching test results for Santa Elena and Ermitaño ores

HIGmill Testwork

HIGmill sizing was accomplished through the signature plot testwork performed onsite using a pilot-scale HIG5 unit as shown in Figure 4 for the following purposes:

1. Generation of the grinding specific energy consumption curve
2. Motor sizing and selection
3. Grinding chamber sizing and selection
4. Determination of specific gravity and bead size for the ceramic media

Figure 4 – HIGmill onsite pilot testing

Figure 5 shows the results of signature plot testing performed on Santa Elena Underground ores (UG), heap leach materials, and a 50:50 blend of UG and heap leach materials. However, during the course of the HIGmill sizing and selection, the Ermitaño ores were not available for the pilot test program. Working from the signature plots shown in Figure 5, the required grinding specific energy was estimated to be at 8.94 kWh/t for a grind down to 50 µm from a feed P_{80} of ~150 µm. Grinding further down to a P_{80} of 35 µm would require a total grinding specific energy of 13.0 kWh/t.

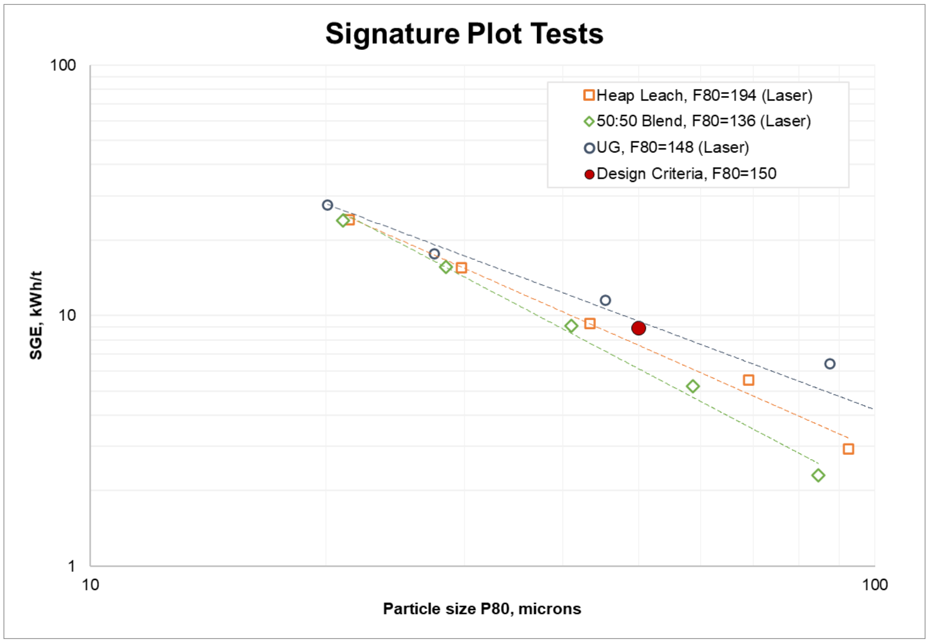

Figure 5 – Fine grinding signature plot

DUAL CIRCUIT PROJECT DEVELOPMENT

Proposed Process Flowsheet

Figure 6 shows the proposed process flowsheet for the so-called "Dual circuit" design concept, which was planned in two stages for execution. The first stage of the project highlighted in blue boxes involves the installation and tie-in of the HIGmill to the existing processes, and the second stage highlighted in red boxes is related to the required plant modifications for debottlenecking downstream processes.

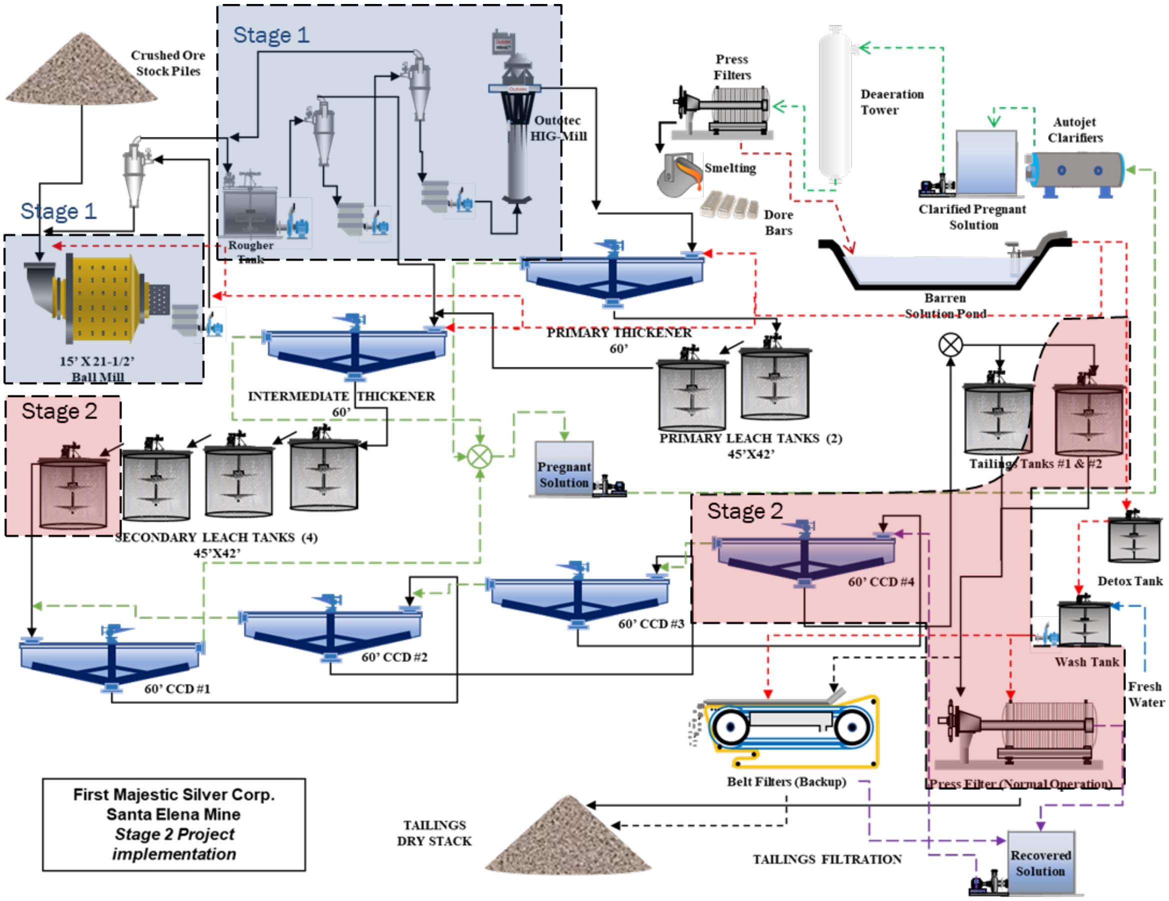

Figure 6 – Proposed Santa Elena process flowsheet

Process Design Criteria

Table 1 shows the general process design criteria for the HIGmill circuit processing Santa Elena ores (including UG and heap leach materials), although the response of Ermitaño ores to fine grinding was not yet known. Based on the testwork and design criteria, a HIGmill size of 1,600 kW with 9,000 L grinding body was selected to provide sufficient grinding power to achieve finer grind size (i.e. 35 µm) if required, also provide a provision for the future ore changes (i.e. Ermitaño ores) while maintaining the grind size at 50 µm level.

Table 1 – HIGmill design criteria

Description	Unit	Value
Mill selected	-	1x HIGmill 1600/9000F
Motor power	kW	1,600
Mill volume	L	9,000
Regrind circuit feed	t/h	120
Cyclone split to UF	%	60
HIGmill feed	t/h	72
Feed P_{80}	µm	150
Product P_{80}	µm	35-50
Slurry density	% solid	55
Solids SG	t/m^3	2.6
Specific energy	kWh/t	8.9-13.0
Grinding media SG	g/cm^3	3.8-4.1
Grinding media size	mm	5-6

Project Planning and Execution

The "Dual circuit" project was strategically divided into two stages (sub-projects), providing a more manageable capital expenditure while unlocking and realizing partial benefits earlier. It was later found that this approach was not only exceeding the original expectations but also help better plan and justify the second stage of the project.

The "Dual circuit" project roadmap is presented in Figure 7. The first stage of the project started with three months of pilot testing on-site in 2017 to size and define the design criteria, followed by six months of engineering and detailed design work (October 2018 – March 2019); after 3 months of engineering design, construction was kicked off with civil and concrete activities (semi-fast-track mode) for a total of 6 months of construction and installation work, resulting in a total of 9 months of execution for the first stage.

During the first half of 2021, the business case and economic model for the second stage of the project were fully developed, leading to the budget approval to proceed with the project in the second half of 2021. Engineering and detailed design kicked off in July 2021 and finalized in December 2021. Construction kicked off in November 2021, with civil and earthworks for the Leaching Tank and the Filter Press. The target project construction end date is the last week of July 2022.

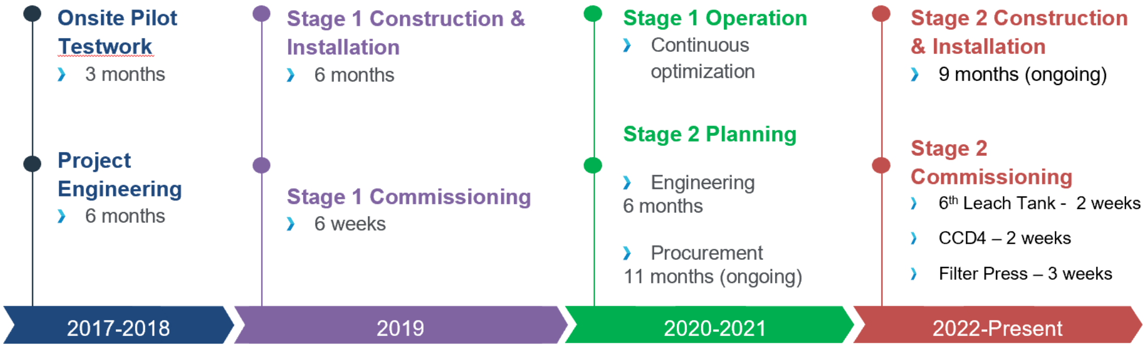

Figure 7 – Dual circuit project roadmap

PROJECT STAGE 1: HIGMILL IMPLEMENTATION & OVERALL GRINDING CIRCUIT OPTIMIZATION

The main components and/or equipment for the first stage of the project consisted of a Variable Speed Drive (VSD) for the existing 15'x21.5' ball mill, a two-stage cycloning for size classification, a 1600/9000F HIGmill operating in an open circuit, one buffer tank, and one safety trash screen.

Installation and Commissioning

The main goal of the first stage of the project was to reduce the particle size P_{80} as much as possible to improve the gold and silver recovery without compromising the continuity of the plant operation. This objective was simple, however, at the time the project was being developed, the Santa Elena Processing Plant was operating at lower than nameplate throughput due to mining constraints, consequently the ball mill circuit was already producing a finer product P_{80} at 70-80 µm. This lower throughput and finer product certainly had its positive effect on metal extractions thanks to longer residence time and improved liberation, as well as its first negative impacts on the horizontal vacuum filters. These positives and negatives were not at the level expected by the implementation of the HIGmill fine grinding at the operation.

An opportunity was then identified during this "first exercise" of fine grinding. Operating a fixed speed ball mill at lower throughputs than originally designed while trying to maintain optimum and/or energy efficient grinding operation was challenging for the operational team. A secondary objective was therefore adopted which is to optimize or reduce energy consumption during the first stage of the project. This could only be accomplished by adding a VSD to the existing ball mill. Now the grinding circuit with two mills capable of varying their operating speed could not only provide the capability to grind finer (the main objective) but also provide a higher level of flexibility to accommodate any throughput variation coming from the mine.

Figure 8 – Ball mill VSD

The installation of the safety trash screen was intended to prevent any coarse oversized material from reporting to the HIGmill feed and remove any trash material from the slurry before further processing. To-date the screen has done very well and removes significant quantities of plastic from the process stream which has the added benefit of assisting Merrill Crowe through a cleaner recirculating process solution stream. The buffer tank ("Rougher" tank) has provided additional residence time for leaching, although the volume is less than a regular leach tank.

Figure 9 – Trash screen and rougher tank

A two-stage classification system with hydrocyclones was added to the circuit prior to the HIGmill, the main purpose was to maintain a high grinding efficiency and minimize over-grinding. A 9000/1600F HIGmill was installed and commissioned to provide the processing plant with the capability to reduce particle size P_{80}, subsequently improving gold and silver recoveries.

Figure 10 – HIGmill and the two-stage classification system

Cold commissioning of the HIGmill began mid to late June 2019, followed by the hot commissioning starting the first week of July 2019. The operational flexibility added within the design of the new circuit combined with the technical expertise in FMSC and contractors' support, allowed the project to complete a successful commissioning in approximately 6 weeks, in which continuous and safe operation was reached by the project and operational team. After the 6-week commissioning period, the new fine grinding circuit was handed over to operation to continue optimizing and improving the metallurgical performance towards reaching the project and operational targets.

HIGmill Operation

The HIGmill was installed and tied into the existing Santa Elena process in July 2019 and has been operating since August 2019. Table 2 summarizes the historical operating parameters of the HIGmill, indicating the level of variability around the circuit. Based on the analysis, it was noted that the operation maintained the HIGmill feed solid density around 50%. During the analyzed operational period, the HIGmill was purposely operated at low operating power to avoid over-grinding and its impact on downstream processes. However, pushing the HIGmill is straightforward and can be done by simply increasing the mill shaft rotational speed and/or increasing the media charge load.

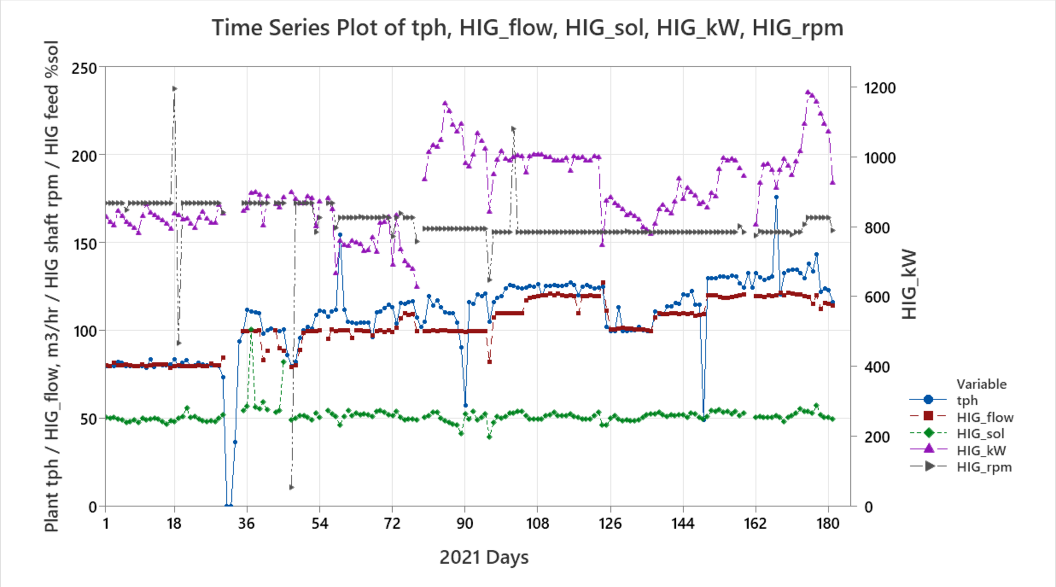

Figure 11 – HIGmill daily average for first 6 months of 2021

Table 2 – HIGmill operating parameters

Variable	Unit	Mean	SE Mean	StDev	CoefVar	Min	Q1	Median	Q3	Max
Plant Throughput	t/h	108	1.7	22.8	21.2	0.0	99.7	111.5	124.6	175.8
HIG feed flow	m^3/h	103	1.1	14.0	13.6	79.1	99.1	100.7	118.5	127.7
HIG feed solid	%	52	0.4	5.1	10.0	39.6	49.7	51.0	52.8	100
HIG power	kW	900	8.4	109.7	12.2	628.3	823.0	880.8	990.8	1185.3
HIG shaft speed	rpm	161	1.3	16.4	10.1	10.5	156.3	158.0	172.8	237.6

As shown in Figure 12, the relationship between applied specific grinding energy and resulting product fineness during the actual operation was found to be in line with the signature plots from the pilot testwork.

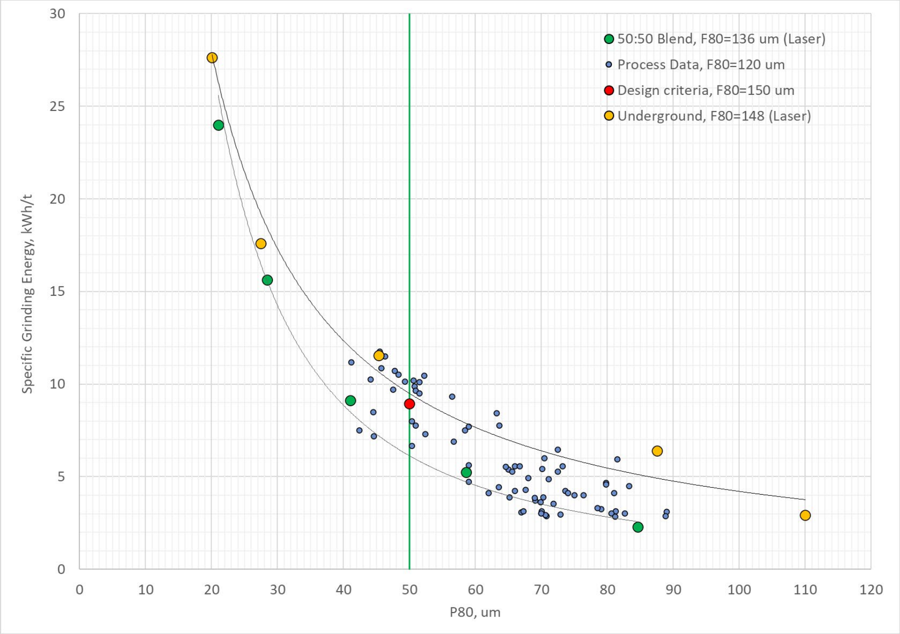

Figure 12 – Operating process data vs signature plots

Metallurgical Performance

As shown in Figure 13, the combination of ball mill and HIGmill produced a P_{80} of 50-60 µm compared to P_{80} of 76 µm with only the ball mill circuit. The inclusion of the HIGmill could allow the circuit to generate a finer product using an equal amount of energy if not less, confirming the energy efficiency of the HIGmill technology.

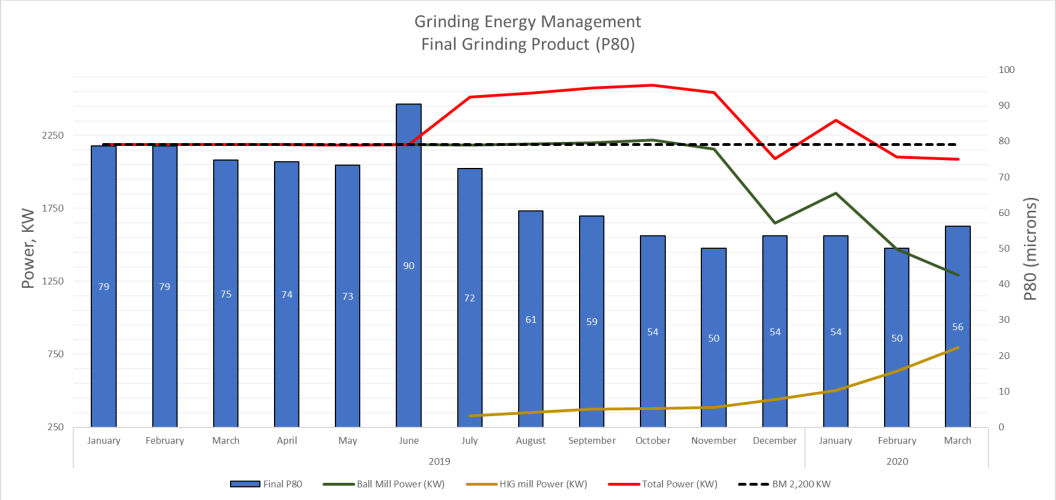

Figure 13 – Impact of HIGmill on grind size

Figure 14 shows the monthly gold and silver recovery data from January 2017 to June 2021, demonstrating increased recovery after the installation of the HIGmill in July 2019. The frequency distributions of the monthly recovery data showed that the average silver recovery increased from 88.8% to 92.8%, and the average gold recovery increased from 95.0% to 95.7%. The gain in recovery and metal extraction is considered partial because of the downstream process limitation. The implementation of the second stage of the dual circuit project will allow the HIGmill to be operated fully therefore further improving the metallurgical benefits as demonstrated in the recovery and grind size relationship from the testwork. In May 2020, the recorded recovery of gold and silver was low because of the Covid-19 impact.

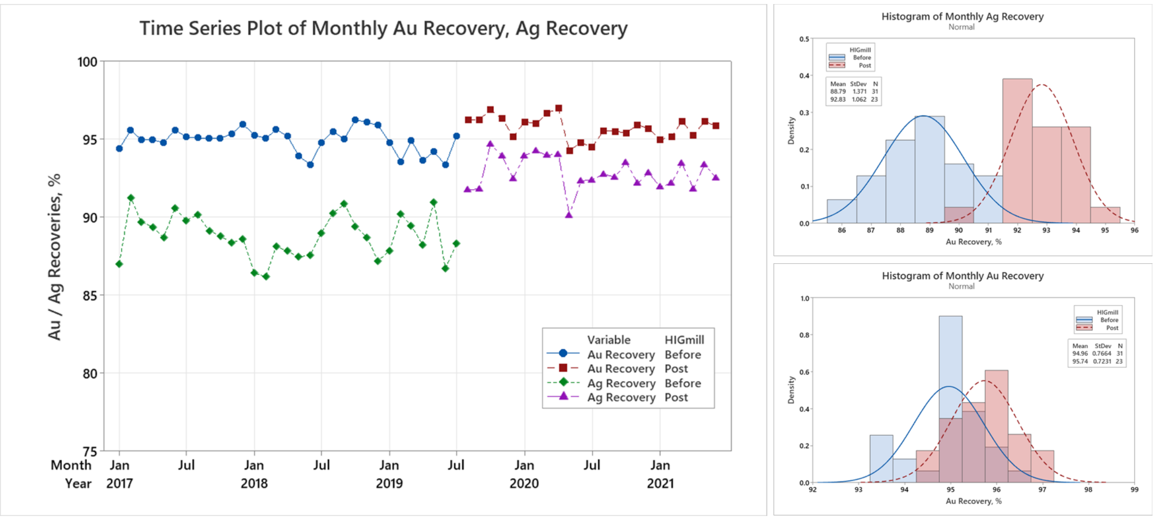

Figure 14 – Improvement on silver and gold recovery

PROJECT STAGE 2: DUAL CIRCUIT DEBOTTLENECKING AND FULL POTENTIAL UNLOCKING

After one and a half years of the fine grinding circuit operation, sufficient operating-process data and experience were collected and used to refine all assumptions made in the development of second stage of the project. This stage of the project consists of a new Leach Tank (1,920 m^3) to increase the overall retention time, a new CCD 18-meter diameter high compression thickener to maintain washing capacity for improved metal recovery, and a new filtration circuit including a new tailings holding tank and a fully expanded 3512 fast filter press 98/98 to handle finer tailings for dry stacking.

Throughput targets above 3,000 t/d and Ermitaño ore leaching kinetics were the main drivers of the inclusion of the sixth leaching tank to the project. Inevitably, higher plant throughput negatively impacts the leaching residence time. In addition, according to the plant maintenance program, one leaching tank must go offline for approximately a week each month which would further impact the silver and gold recoveries. Furthermore, it has been proven that Ermitaño ores have slower kinetics compared to Santa Elena's, even at finer particle size distributions, this makes even more beneficial to install the sixth leaching tank to the plant, as part of the full potential unlocking efforts.

Figure 15 – Leach Tank #6 construction progress, January 2022

The settling rates in the existing high-rate CCD thickeners are expected to slowdown as a consequence of the finer particle size distribution, resulting in lower underflow densities which could potentially affect downstream filtration process. A high compression thickener functioning as the 4th CCD, will provide not only the ability to improve washing efficiency within the circuit, but also the capability to manage finer particle sizes more efficiently, assuring the proper underflow slurry densities before filtration.

Figure 16 – CCD4 thickener earthworks progress, January 2022

Ultimately, the fast filter press will provide the ability to process fine and ultrafine particle sizes while delivering a proper final moisture content, that is suitable for dry stacking.

Figure 17 – Fast filter press circuit construction progress, January 2022

LESSONS LEARNED

Design and Implementation Phase

- Technology selection and equipment sizing

    - HIGmill was selected for the fine grinding duty to provide flexibility that could accommodate the variation in feed rate, ore hardness, and grind size target. One major advantage of using HIGmill is the turndown ability via VSD, particularly during the first stage of the project when the downstream filtration capacity is the main process bottleneck. The operation can simply run reduced HIGmill speed to avoid over-grinding.
    - The original testwork for HIGmill sizing was primarily done for Santa Elena ores. However, the decision to select a HIGmill with a larger motor size was made for the consideration of finer grind requirement and future ores with increased competency and hardness.
- <u>Flowsheet development</u>
    - Various bypasses were considered and incorporated into the design to provide a higher degree of flexibility for commissioning and different operating scenarios.
    - A trash screen is recommended to eliminate unwanted oversize and trash material from entering the HIGmill.
- <u>Auxiliary equipment</u>
    - Mill start-ups would require additional pumping power to break through the ceramic media bed before the steady slurry flow is obtained. The back pressure from the charge load is a key consideration in selecting the HIGmill feed pump and motor.
    - It has been challenging to get accurate readings consistently from non-nuclear densitometers, adding difficulties for reliable process control and automation.
    - High variability has been found on the "clamp-on" flowmeters mounted on the slurry lines.
    - Manual knife gate valves are not recommended, all manual valves from the original installation have been changed to automatic valves.

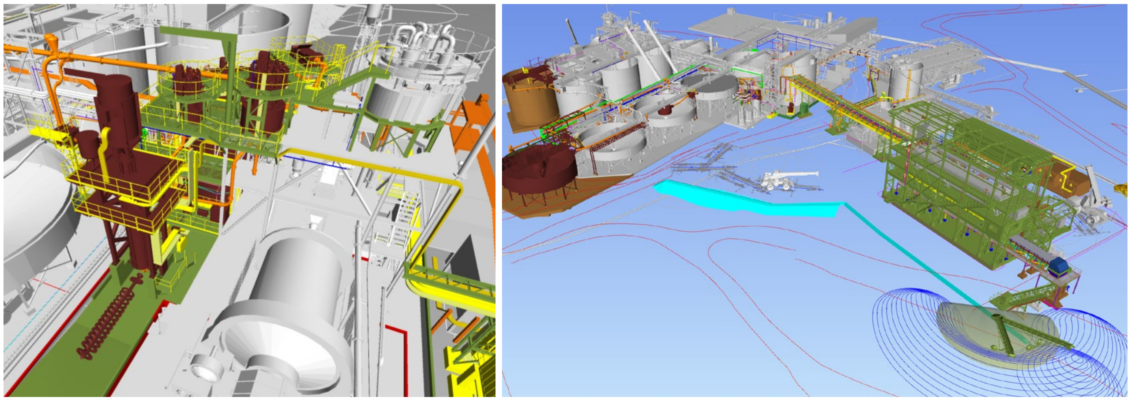

Figure 18 – Design of the dual circuit in two stages

- <u>Installation and commissioning</u>
    - The HIGmill is manufactured and fabricated in Europe, some specialized tooling and materials for the installation were difficult to find in Mexico.
    - Experienced personnel is key to assure proper, safe installation and preventing any project delays.

Figure 19 – HIGmill installation and commissioning

Post Implementation Phase

- HIGmill startup "hiccups"
    - **Learning curve:** for a processing plant that has operated a single ball milling circuit, it was certainly a challenge not only to the operating personnel but also for the management staff to implement a new/innovative technology that has considerably more instrumentation, controls, and very different operating procedures. Constant involvement of the corporate commissioning team and equipment experts' support were the key to reduce the learning curve, however, an extensive training program would've been an alternative solution to have a more "relaxed" ramp-up period. This project took a fast-track approach for the execution, as a result, the project team had only one opportunity to visit a similar HIGmill implementation in Mexico. And only a portion of the operating personnel received the comprehensive training, which made things a bit more challenging.
    - **Control philosophy and sequences**: for people at the site to get comfortable with unknown control philosophies and operating sequences took a considerable amount of time. There has been constant anxiety on the operators that prevents them from taking immediate actions and/or decisions when required. Extensive and longer training programs could've helped with this matter.
    - **Site involvement and ownership:** the project delivery transition period was somewhat complicated. Unlike other common conventional technologies (e.g. ball mills), there are only 2 or 3 HIGmill installations in entire North America. It took additional time and effort for the site operational team to take the full ownership of this innovative technology because of lacking confidence and knowledge of this innovative technology.
- HIGmill operation and control
    - There are three common control modes, namely 1) power draw mode, 2) SGE mode, and 3) product PSD mode. Santa Elena is currently operating it's HIGmill based on mill power draw. There are some advantages to moving to SGE control after completing the second stage of the project.
    - The current media dosage is manually controlled based on the HIGmill product particle size distribution (current target P_{80} is 50 μm). Current HIGmill operating parameters are averaged at 50% media load and 50% solid density in the feed. The mill speed is varied based on the desired mill operating power defined by the metallurgical team.
- Media retention system
    - The initial design had no safety screen on the HIGmill discharge. The media overflowing became problematic during the initial operation. The operation started the retention system by installing a vibrating screen on the HIGmill discharge, which not only prevent the media losses, but also helped the following issues that operation encountered:

        - The retention system was making reloading media faster after maintenance downtime. New pumps were installed to send the media back automatically.
        - The HIGmill discharge was initially gravity feeding the thickener feedbox and was not flowing fast enough which led to build-up in the pipe. The retention system allowed the operation to mix the rougher cyclone overflow and HIGmill discharge in the screen undersize tank and pump to the thickener feedbox.
        - The retention system could capture any broken-off liners that exit out the mill. It helped the maintenance crew to monitor the system.
    - Based on Santa Elena's experience, the safety screen(s) on HIGmill discharge are highly recommended.
- <u>Wear components</u>
    - Original grinding rotors were hardcast metal and were later changed to rubber lined as steel did not last very long. At first the life of the rotors was almost doubled in some sections of the HIGmill.
    - With current operating conditions, bottom section and upper section are the ones that wear out faster, however, rotors order are shifted to make the most of the middle section as well.
    - Once the second stage of the project is completed and there is no downstream problems due to fine grinding, operating the HIGmill with a higher charge load and variable mill speed could be favorable from operating cost perspective.

Figure 20 – HIGmill operation at Santa Elena

- <u>Fine grinding impact on existing equipment</u>
    - **Thickener operation:** the settling rates have changed since the implementation of fine grinding circuit. On one hand, we have the -20 μm stream scalped out prior to the HIGmill feed as part of the dual circuit, that has a very slow settling rate and high turbidities in the thickeners overflows, presenting the need to increase flocculant additions and the level of compaction achievable by the existing high rate thickeners without having operational problems was reduced, resulting in lower underflows % solids overall. On the other hand, we have the HIGmill product, which even at finer grinds present a very amenable settling rates and compaction levels, very easy to manage by the existing equipment even compared to coarser grinds prior to the HIGmill implementation. In some areas the two different streams are treated separately and later mixed to improve the thickener performance overall.
    - **Filtration operation:** for a horizontal vacuum belt filter that was originally designed to operate with particle sizes P_{80} in the order of 100-120 μm, certainly fine grinding has had a negative impact on the performance of the equipment; final cake moistures have gone from 18-20% at 100+ μm to 28-30% at 50 μm.
    - **Merrill Crowe operation:** with higher turbidities coming out of the thickeners and higher floculant dosages, the solution cleaning cycles in the autojet clarifiers of the Merrill Crowe have been reduced from 20-22 hours to approximately 15 hours, resulting in slightly higher

filter aid consumption and increased effort from the operators. Precipitation efficiencies having been affected so far by the fine grinding.

- **Viscosity effect on existing equipment:** one of the most noticeable changes on the slurry characteristics since the implementation of the fine grinding circuit, is the viscosity. It is not an operating practice at the Santa Elena processing plant to measure this attribute. However, the changes in viscosity is evident; specially when treating the rougher cyclone slimes separately (-20 µm). One can easily find that the pumps performance is affected, levels of agitation in the leach tanks seems somewhat slightly reduced and even the oxygen diffusion is negatively impacted (less concentrations while maintaining same dosages). With the help of external resources (suppliers, universities, etc), a few measurements have been made using different equipments in an effort to get a better understanding on how viscosity is affecting the process and what strategies can be implemented to prevent any negative impact, however, a big area of opportunity lies on this subject and is intended to be further investigated.

SUMMARY AND CONCLUSIONS

Since the installation of the HIGmill in July 2019, the Santa Elena processing plant has benefited from improved gold and silver recoveries. A greater benefit has been observed when processing the Ermitaño ores due to its increased ore hardness and finer grind requirement. Despite the challenges encountered in installation and operation of the HIGmill, continuous efforts have been given to further optimization of the circuit by implementing best operating pracrices, and working towards advanced process control and automation.

The experience gained from executing the first stage of the project followed by a successful operation have provided a strong justification to transition to the next stage of the project, which is currently working in progress. Upon the completion of the second stage of the project, unlocking the full potential of the HIGmill technology could be realized.

Going forward, there is an opportunity to add another HIGmill in parallel with the existing HIGmill to further support the plant expansion at Santa Elena mine thanks to the additional ore resources from the Ermitaño mine.

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REFERENCES

Nielsen, B., Lehto, H., Musuku, B., (2016) Design, Installation, Comissioning and Operation of Fine Grinding Technology at the Kevitsa Mine, In: 13th AUSIMM mill operators' conference, Perth WA 10-12 Oct., 2016.

Paz A., Ghattas, R., Loro, S., Belke, J., 2019, Fine Grinding Implementation at The Cracow Gold Processing Plant, MetPlant 2019, Perth WA, 9 - 10th September 2019.

Paz, A., Ypelaan, C., Ryan, T., & McInnes, MDeHart. (2021). *The Application of Ultra Fine Grinding for Sunrise Dam Gold Mine*. Paper presented at the AusIMM Mill Operators Conference June 2021.