Adding HIGmill Technology to the Ero Copper Caraiba Concentrator

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Abstract

Ero Copper operates the copper mining complex at Pilar, Bahia State, Brazil, through their Ero Brazil-owned MCSA Caraiba operation. Ero Copper acquired the mining complex in late 2016 and has aggressively grown the operation and extensively drilled the mining lease to identify a growing sustainable mining resource in the future.

The existing plant was built and operated initially in 1979 and 1980; the original capacity was 5.5 million tonnes per annum (Mt/a) with ore feed from the Pilar underground and Surubim open pit mines.

To cater to an expansion plan from the milled production level of ±1.8 Mt/a in 2017, the concentrator plant is being sequentially debottlenecked, expanded, and optimized in various stages to achieve 4.2 Mt/a by 2024.

The first phase increased plant throughput from the FY 2017 level of 1.77 Mt/a, at a head grade of 1.31% copper, a copper recovery of 86.8%, and 20,133 tonnes of copper produced in concentrate, to FY 2021, when throughput was 2.37 Mt/a, at a head grade of 2.01%, and copper recovery of 92.4%. The major element involved adding a HIG stirred mill into the existing circuit to improve metallurgical performance, copper recovery, and mill circuit capacity.

The operation recorded operating data for FY 2022, of 2,864,230 tonnes milled, at a head grade of 1.76% copper, with 46,371 tonnes of copper sold in concentrate. Plant recovery was 91.9%.

This paper compares the Phase 1 expansion target with the current plant operating data, especially the impact of the HIGmill on the overall plant performance such as increased copper recovery.

Keywords

Ero Copper Corp, Ero Copper Brazil, Caraiba, HIGmill

Introduction

Ero Copper Corp. (the Company) is a publicly listed copper mining company in Vancouver, British Columbia, Canada, that trades on the Toronto and New York Stock Exchanges. Ero Copper's principal asset is a 99.6% interest in Mineração Caraíba S.A. (Ero Brazil), a mining complex in the Curaçá Valley, northeastern Bahia State, Brazil.

The Caraíba Mining Complex operating history started in 1979 in the region with open pit mining and processing operations. The Caraíba mill was originally designed to process ore from the open pit mines at a rate of 5.5 million tonnes per annum (Mt/a). Underground mining operations commenced in 1986 with the Pilar UG Mine utilizing a production shaft supported by two primary underground jaw crushers. Ore from throughout the Curaçá Valley (including within the Vermelhos and Surubim Districts) is crushed using a primary gyratory crusher on the surface.

The Mineração Caraíba acquisition process started in December 2016, and in December 2017, the Ero Copper Corp. acquired additional shares of Mineração Caraíba, increasing its ownership interest in Mineração Caraíba to 99.6%.

In mid-2018, the Company initiated an optimization program aimed at improving metallurgical recoveries and overall plant performance. Seymet metallurgical consulting conducted a detailed analysis of plant operations, operating data, historical metallurgical testwork information, and in-house metallurgical resources.

This work included updated mineralogical characterization and liberation analyses. These studies paved the way for the introduction of HIGmill technology. A road map to achieve optimized copper recovery was identified subsequently and a testwork program was initiated.

The first part of this optimization plan is described in this paper: the introduction of HIGmill technology at Caraíba.

In 2022, Mineração Caraíba undertook a rebranding initiative and is today known as Ero Brazil.

The Pilar District is approximately 385 kilometers (km) north-northwest of Salvador and 90 km southeast of Petrolina, in the State of Bahia (Figure 1). The regional Ero Brazil operations in Bahia state include three active, producing mining locations, and the existing processing operations. The active operations include the underground Pilar mine, the underground Vermelhos mine, the Surubim, mine and the integrated Caraíba metallurgical complex.

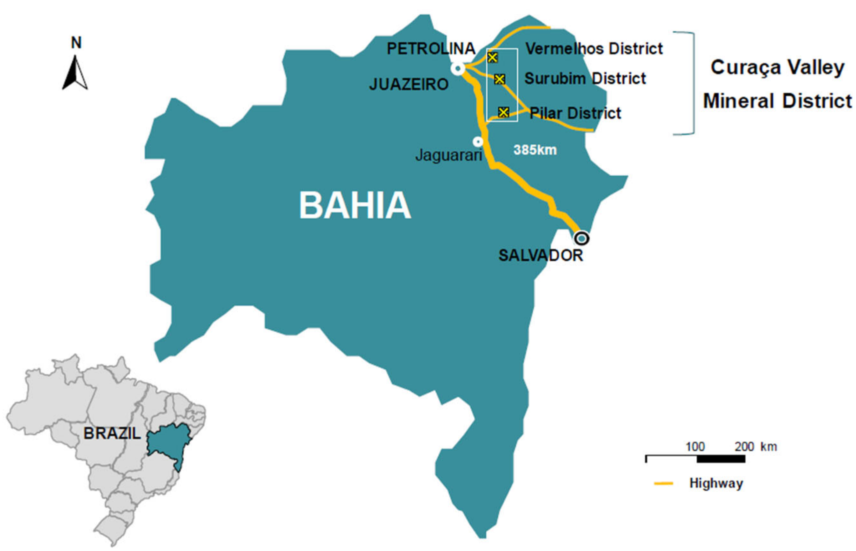

Figure 1—Location of the primary mineral districts, Caraíba Operations, Bahia State, Brazil

Ero Brazil continues to explore the highly prospective Curaçá Valley lease area. This is integral to the future expansion strategy for the Caraíba Operations.

The geology in the region is mainly high-grade mafic–ultramafic mineral occurrences. Feed ore is currently processed at an installed capacity of 3.2 Mt/a, using conventional crushing and flotation at the Caraíba mill adjacent to the Pilar underground mine. Typical feed grades vary between 1.25% and 1.54% copper resulting in a high-grade, clean concentrate grading approximately 32% to 35% copper. The concentrate is shipped and sold locally to the Paranapanema Smelter and international markets via the Port of Salvador.

Background

The Caraíba mill was originally designed for 5.5 Mt/a of open pit feed, and in 1986 underground operations commenced. The mill was designed with a conventional flowsheet, including primary, secondary, and tertiary crushing circuits to a mill feed of 80% passing (P_{80}) 10 millimeters (mm). The crusher product is fed utilizing a stacker reclaimer system to four 3000 kilowatts (kW) ball mills from shared silos. The ball mill cyclone overflow (COF) of 120–140 microns (µm) was fed to a conventional rougher, cleaner, cleaner–scavenger, and re-cleaner circuit.

The Caraíba mill flowsheet changed significantly over the years since commissioning in 1979. Then the flowsheet consisted of a conventional three-stage crushing circuit, four primary ball mill circuits, and a conventional flotation circuit that included a rougher, cleaner, cleaner–scavenger, and re-cleaner stage. The typical flotation feed size was F_{80} 140 µm. Figure shows a simplified flowsheet.

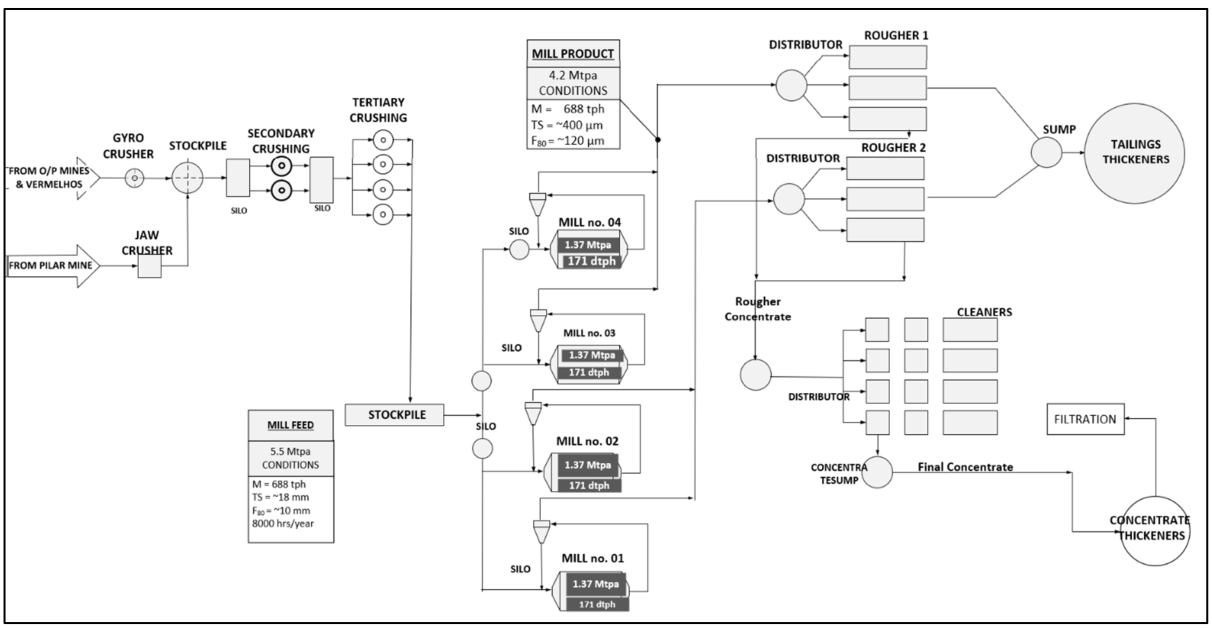

Figure 2—Original Caraíba flowsheet

The circuit was changed to the flowsheet shown in Figure in stages over the years. Two ball mills were sold, later Derrick screens were installed on the COF lines to feed a smaller regrind ball mill and later a Metso-Outotec Vertimill.

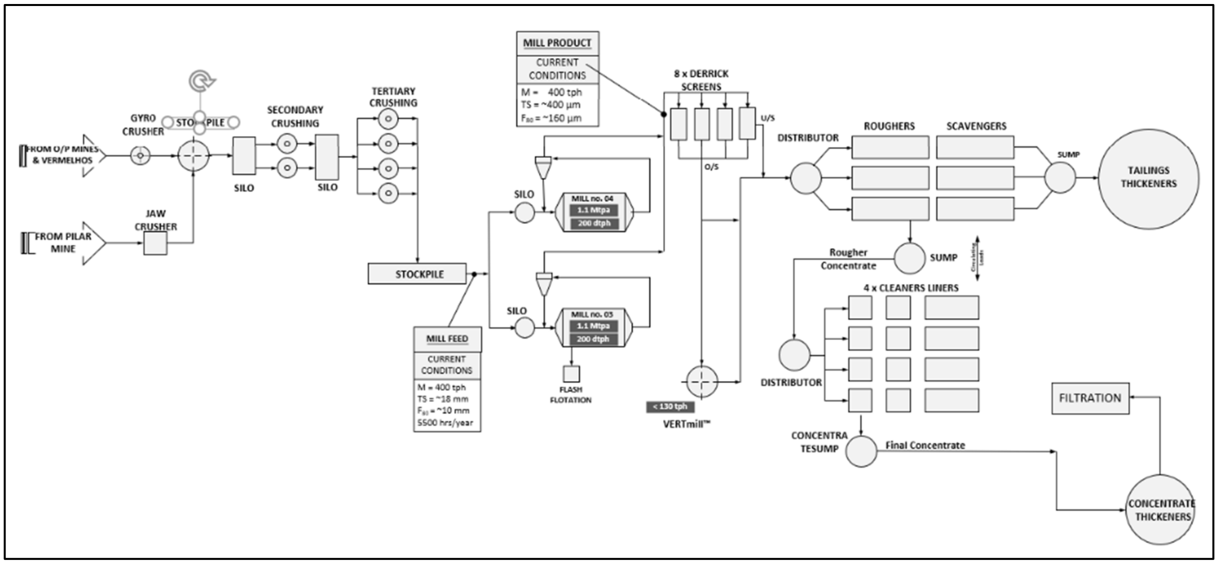

Figure 3—Caraíba flowsheet indicating the two ball mills, Derrick screens

These regrinding systems were underpowered and could not achieve the required comminution for the targeted flotation feed of F_{80} 110 µm. The two remaining ball mills at feed rates of 200 tonnes per hour (t/h) each, produced COF of P_{80} 160 µm.

Table 1 shows the production profile from 2011, indicating the annual throughput, feed grade, copper production, and recoveries. The table shows the relatively low recoveries in the years up to 2019.

Table 1—Caraíba mill throughput, feed grade, and recoveries from 2011 to 2019

Year	Tonnes	Grade (% Cu)	Copper Production-tonnes	Recovery (%)
2011	2,749,812	1.09	25,096	83.7
2012	2,717,980	1.07	24,827	85.4
2013	2,940,566	0.91	22,494	84.3
2014	3,014,269	1.01	25,717	84.7
2015	2,836,528	1.11	27,046	86.0
2016	826,759	0.71	4,895	83.5
2017	1,771,209	1.31	20,133	86.8
2018	2,257,917	1.56	30,426	86.3
2019	2,424,592	1.93	42,318	90.5

The operation ran in this configuration up to 2018 when a recovery optimization study began. The study's objective was to identify areas of recovery losses and possible technological solutions for these areas. Inadequate liberation was identified as one of the main reasons for recovery losses. SJT MetMin Services (Pty) Ltd. (SJT MetMin) of South Africa and the University of Sao Paulo, Brazil, conducted mineralogical and liberation studies. Fractional analyses of the plant samples and data showed that copper recovery diminished at coarse particle sizes in the flotation feed, confirming the need for further regrind to improve copper recovery. The next section covers the testwork and liberation studies carried out during the optimization study.

Project Initiation: Sample Analyses—Mineralogy

As stated above, in September 2018 the Company initiated an optimization program aimed at improving metallurgical recoveries. The main objectives were to update the mineralogical characterization of the Company's flotation feed, concentrate, and final tailings, and to understand the grind size and liberation analyses on flotation feed, concentrate, and tailings samples. SJT MetMin and the University of Sao Paulo performed the testwork on monthly plant composite samples. This initial characterization program was completed and a second phase of tests was carried out using a series of composite samples collected from the oversize fraction of the Derrick screens during plant operations. These samples were subjected to particle-size characterization and grind-versus-recovery testwork at Mintek's testing facility in Randburg, South Africa.

Verification testwork was conducted in the Caraíba mill in March 2019. The objective was to validate the expected improvements in recovery at the target grind size of P_{80} 75 µm.

MINERALOGICAL CHARACTERIZATION TESTWORK

Final copper concentrate and final tailings samples from the Caraíba mill were characterized mineralogically. This chemical analysis for total copper and trace elements, X-ray diffraction (XRD), scanning electron microscopy coupled with energy-dispersive spectrometric (SEM–EDS) analysis, and phase quantification of liberation and mineralogical composition.

XRD analysis indicated that the main copper-bearing phases in the tailings sample (0.23% Cu) detected primarily chalcopyrite as the copper-bearing phase, with minor bornite. The concentrate sample (37% Cu) contains chalcopyrite, bornite, and cubanite. Gangue minerals in both the concentrate and tailings samples are pyroxene, plagioclase, talc, quartz, and mica (biotite/phlogopite).

SEM-EDS analysis of both samples confirmed the primary copper-bearing phases of chalcopyrite, cubanite, and bornite, with trace amounts of chalcocite, digenite, and covellite. Figure shows the gangue phases in the concentrate sample in the −75/+150 µm fractions.

Figure 4 shows that copper sulfides represent 40% of the mass in the +150 µm fraction and 65% of the mass in the +75/−150 µm fraction.

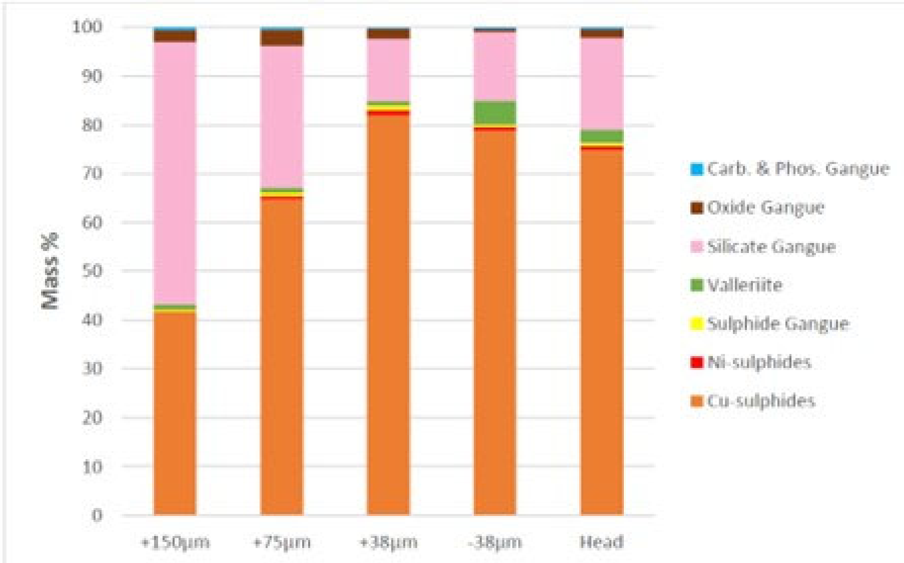

Figure 4—Mineralogical composition, by size fraction for concentrate (Coetzee, 2018)

Figure supports the data and shows the copper grade in each size fraction. The results showed:

- 43% of the total contained copper in +38/−75 µm size fraction
- 32% of the total contained copper in +75/−150 µm size fraction
- 20% of the total contained copper in +150 µm size fraction.

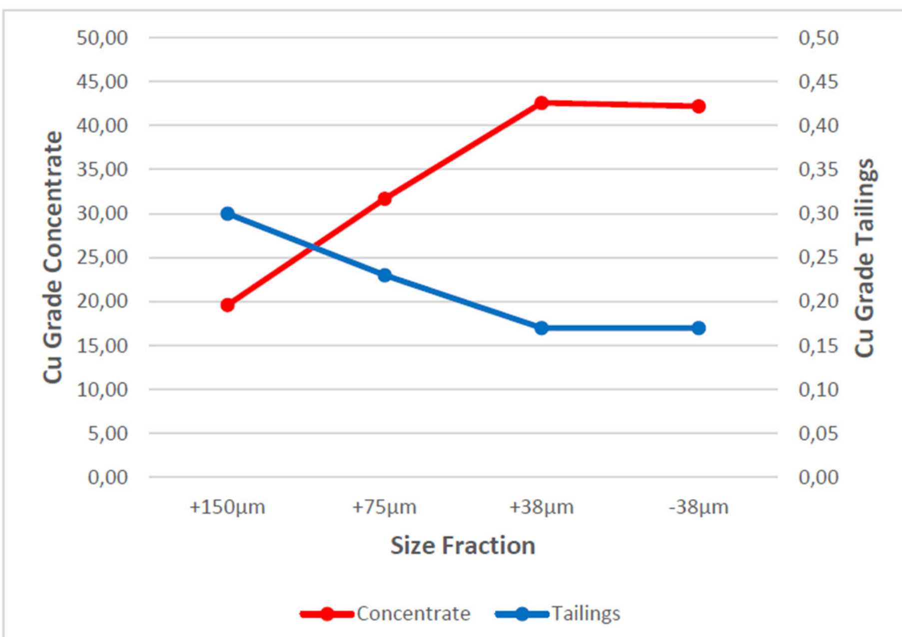

Figure 5—Mineralogical composition, by size fraction for tailings (Coetzee, 2018)

The data show the presence of un-liberated gangue in the coarser size fractions of the concentrate sample.

Figure shows the mineral phases in the tailing samples, with the bulk phase as silicate gangue. The data are inverse, with the concentrate sample indicating higher copper grades in the coarser fraction.

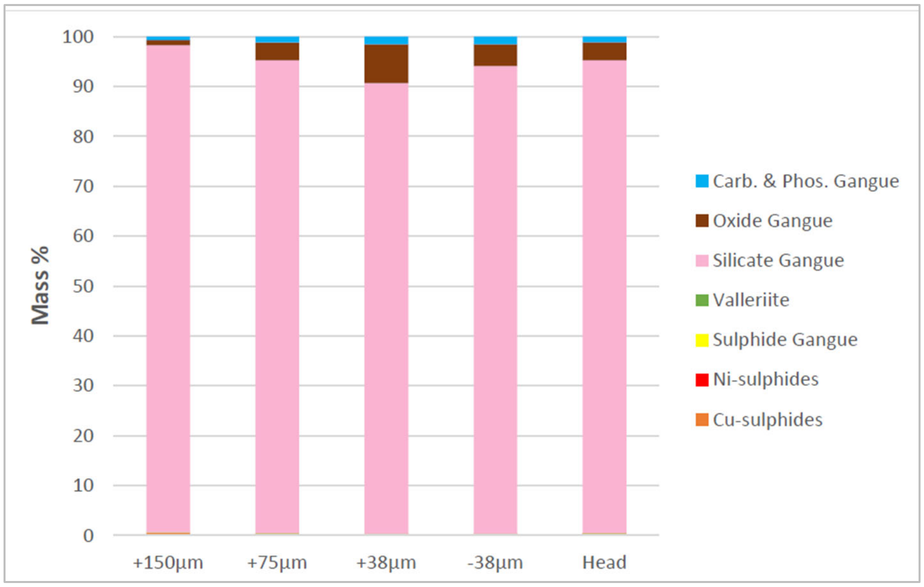

Figure 6—Mineralogical composition, by size fraction for tailings (Coetzee, 2018)

The tailings sample indicated most of the copper-bearing sulfide minerals were within locked or middling composite particles. The data also shows the +75 µm size fraction represented approximately 62% of the tailings sample mass, and had a calculated copper grade of 0.26% compared to the −38 µm size fraction, which had a copper grade of only 0.17%. The +150 µm size fraction represented approximately 30% of the tailings sample mass and had a calculated grade of 0.30% copper. Similarly, the liberation analysis of the tailings sample pointed to a significant potential improvement in overall liberation and recoveries with re-grinding the +75 µm size fraction.

INITIAL LIBERATION TESTWORK WITH ROUGHER FLOTATION

A composite sample of Derrick screen oversize material was analyzed for liberation response. Subsamples of the composite were milled using a laboratory batch-stirred test mill to achieve the target grind size for rougher flotation testwork. Laboratory rougher flotation tests were conducted at Mintek (Ford, 2019). Flotation concentrates and final tailings samples were assayed using inductively coupled plasma optical emission spectroscopy. Laboratory rougher flotation testing was conducted at varying grind sizes and, as a baseline, with no regrinding.

The size fractions tested were P_{80} 280 µm (baseline with no regrind), 150 µm, 125 µm, 106 µm, 75 µm, and 53 µm. Figure indicates that any degree of regrinding improves rougher performance. The rougher recovery compared to the baseline-with-no-regrind sample, for grinds of P_{80} 150 to 106 µm showed recoveries of 78% to 80%. Grinding to P_{80} 75 µm increased overall recovery to around 84%.

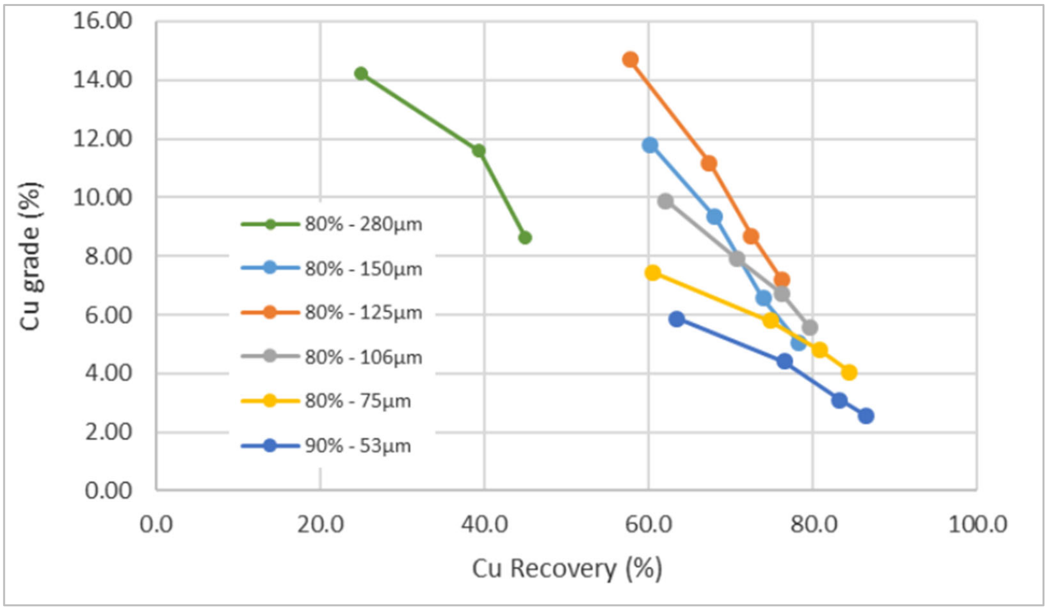

Figure 7—Rougher concentrate grade vs. recovery curves at various grind sizes (Ford, 2019)

CARAÍBA MILL VALIDATION TESTWORK

Additional testwork, undertaken by MCSA in March 2019, sought to validate and further quantify the expected improvement in recovery with a finer grind of the Derrick oversize material, which constitutes feed for the regrind circuit. Over the period of six operating days, with the Caraíba mill operating at close to its current installed capacity (approximately 9,600 tonnes per day), representative samples of mill feed, Derrick screen oversize, and Derrick screen undersize were collected for additional testing. The samples, which ranged in copper head grade from 1.45% copper to 2.38% copper, were tested for rougher flotation recoveries before and after regrinding the oversize fraction to P_{80} 74 µm.

The laboratory rougher flotation testwork sought to simulate the residence time, reagent types, and dosages of the rougher flotation cells currently in use in the Caraíba mill. The results, shown in Table 2, highlight an average 16.1% increase in rougher recovery for the Derrick oversize fraction, resulting in a total increase in metallurgical recovery of between 3.7% and 4.9% copper. A 3.0% increase in metallurgical recoveries has been forecasted commencing from 2021, commensurate with commissioning and integrating the HIGmill.

Table 2—Results of MCSA validation testwork

	Copper Grade (Cu%)			Cu Recovery without Regrind			Cu Recovery with Regrind of O/S			Improvement
Sample	**Feed**	**Oversize**	**Undersize**	**Oversize**	**Undersize**	**Total**	**Oversize**	**Undersize**	**Total**	**Total Rec.**
22-Mar-19	1.5%	1.1%	1.6%	72.3%	95.0%	89.6%	92.7%	95.0%	94.5%	4.9%
25-Mar-19	1.9%	2.3%	1.7%	82.0%	94.6%	89.5%	92.7%	94.6%	93.9%	4.3%
26-Mar-19	2.1%	2.3%	2.0%	90.4%	95.0%	90.4%	92.4%	95.0%	94.1%	3.6%
27-Mar-19	2.4%	1.9%	2.7%	78.0%	94.2%	90.0%	92.7%	94.2%	93.8%	3.7%
28-Mar-19	2.3%	0.9%	3.0%	64.6%	93.8%	90.0%	92.8%	93.8%	93.7%	3.7%
29-Mar-19	1.5%	0.9%	1.8%	72.0%	94.0%	89.4%	92.6%	94.0%	93.7%	4.2%

CARAÍBA HIGMILL TEST PROGRAM

A technology trade-off was conducted to select the required regrinding system. Previous testwork and trade-off studies comparing the Vertimill and the HIGmill, and the HIGmill was selected based on several criteria. One main consideration was that the HIGmill could fit inside the current ball mill building under the existing craneage, whereas the Vertimill with its classification system had to be positioned outside the building due to its height and larger footprint. HIGmill operates in an open circuit configuration without recirculating loads with slurry passing through the multiple grinding zones with no particle short-circuiting and no requirement for recycle streams.

Several HIGmill tests were performed based on the mineralogical work, initial laboratory liberation studies, and flotation testwork. The baseline tests for mill sizing were performed with a HIGmill, 200 liters (L)/75 kW, HIG75 to specify the specific grinding energy (SGE), in kilowatt-hours per tonne (kWh/t). The sample received had F_{80} 290 µm and solids specific gravity (SG) = 2,89 grams per cubic centimeter (g/cm^3). The sample weight received was approximately 2,500 kg, and a semi-continuous test was completed with 600 kg samples.

The operational parameters (Heiskari -2019):

- Grinding media (beads) filling rate: 50% of mill grinding chamber volume
- Ceramic grinding media SG: 3.9 g/cm^3
- Media charge: 70% 4-5 mm beads, 30% 5–6 mm beads
- Milling density: 55% w/w solids, corresponding to a slurry density of 1.56 kg/L.

Table 3 summarizes the HIGmill tests completed during the project design phase. Test 1 showed a very low SGE, and during an investigation, it was found that the sample was circulated a few times through the pump which resulted in additional energy used during these tests. The remaining test data were more in line, and the recommended SGE for the design was 14.7 kWh/t.

Table 3—Summary of HIGmill testwork completed (Heiskari -2019, Roitto -2019)

Test nr	1[1]	2a	2b	2c	3a	3b
HIG Test mill	HIG 5	HIG 5	HIG 5	HIG 5	HIG75	HIG75
F_{80} (µm)	284	280	280	280	290	290
Solid SG	2.89	2.87	2.87	2.87	2.89	2.89
SGE (kWh/t)	6,4	13.1	13.72	14.14	13,85	9,60
P_{80} (µm)	75	75	83	75	70	81

Note: nr =number of tests.
[1] additional energy applied, not recorded during pumping stages

Table 4—Comminution characteristics of the Caraíba mill ore (Pereira -2021))

Testwork	Unit	Average	Standard deviation
Bond Abrasion Index (Ai)	g	0.32	0.14
Macron Abrasion Index (Ai)	g/t	1,168	290.4
Macron Crushability (Cr)	%	41.1	6.84
Crushing Work Index (CWi)	kWh/t	18.9	1.88

Testwork	Unit	Average	Standard deviation
BWi Test			
Closing Screen	mm	0.15	-
Work Index (BBWi)	kWh/t	17.9	2.05
Drop Weight Test			
A	-	90	8.31
b	-	0.6	0.17
ta	-	0.4	0.09
SAG Circuit-Specific Energy	kWh/t	9.7	1.05

THE 2019 HIG MILL PROJECT

This section covers the HIG project details concerning scope, cost, and schedule.

SCOPE AND PROJECT WORK

The project's main objectives were:

- Solution to be fast-tracked
- Low capital expenditure
- Minimal operating impacts on existing plant operations
- Use of existing infrastructure and real estate
- Use of existing services and proximity of power, water, and process reticulation.

The project was initiated in June 2019, with an Engineering, Procurement, and Supervision (EPS) contract with Metso: Outotec. The EPS contract was for a HIGmill regrinding plant, including a HIG2300/23000F with all necessary auxiliary equipment, E-Room, motor, variable-speed drive, and site advisory and supervision services.

Figure shows the simplified flowsheet, indicating the HIGmill position. The HIGmill receives feed from the current Derrick Stack Sizer screens oversize. The HIGmill product will join the Derrick screen undersize stream that is distributed to the flotation circuit roughers. Scope includes the feed tank, pumps, feed, and product sample systems, particle-size analyzer (PSI 1500), and media feeding system.

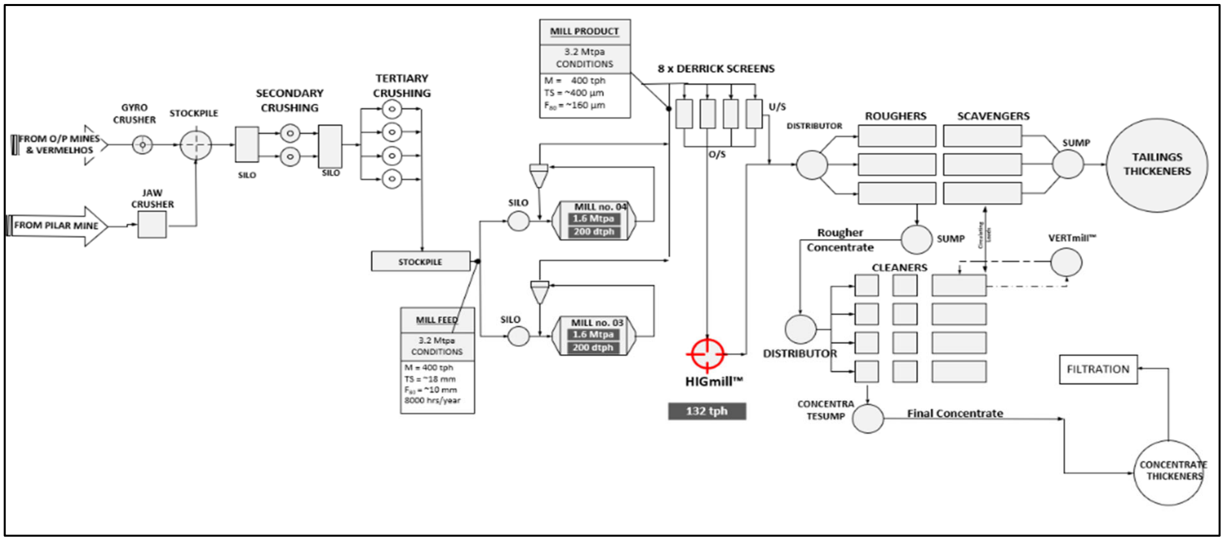

Figure 8—Caraíba mill flowsheet indicating the HIGmill

Table 5 shows the main design criteria for the HIGmill. The HIGmill had to operate in a wide range of throughputs. This was to cater to conditions when one ball mill is down, and additional feed could be added by bypassing some of the Derrick screens. The SGE, as discussed in the testwork section, was updated with additional tests.

Table 5—Main design criteria for the HIGmill

Variable	Unit	Parameter
Minimum Feed Rate to the HIGmill	dry t/h	113
Maximum Feed Rate to the HIGmill	dry t/h	166
Design Feed Rate to the HIGmill	dry t/h	207
New Feed Specific Gravity	t/m^3	2.95
Top Size (New Feed to Mill)	µm	~450
F_{80} (New Feed to the Mill)	µm	~280
Desired P_{80} (jn the Mill Final Product)	µm	~75
New Feed Specific-Energy Consumption	kWh/t	Original test: 7.6 - 10.7; Updated test : 14-16
Feed Slurry Density Range	t/m^3	1.52 to 1.79

The HIG 2300/23000F was selected based on the design criteria and included: a gearbox with oil lubrication and an oil-to-air cooling unit, supporting structural steel, a mill shaft assembly fully equipped, a grinding media hopper, and E-room. The shaft configuration originally selected included a lined shaft bottom cap, wear-resistant rubber cranked castellated grinding rotors (GrindForce grinding mechanism) in the grinding media bed, and cranked non-castellated grinding. Figure shows the plan view of the HIGmill installed relative to the ball mills. The plan also shows the position of the feed silos and the Derick screen building that was added later.

Figure shows the side view of the HIGmill in position. The drawing shows the relative height of the HIGmill. The existing mill aisle crane is used for installation and maintenance.

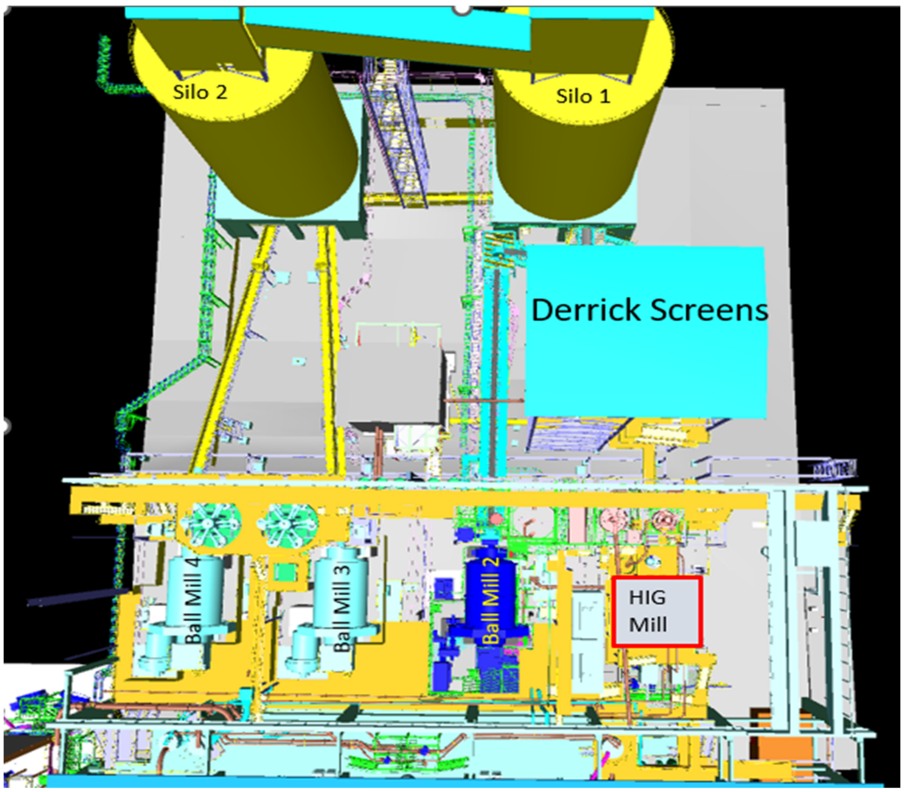

Figure 9—Plan view of HIGmill footprint relative to the installed ball mills

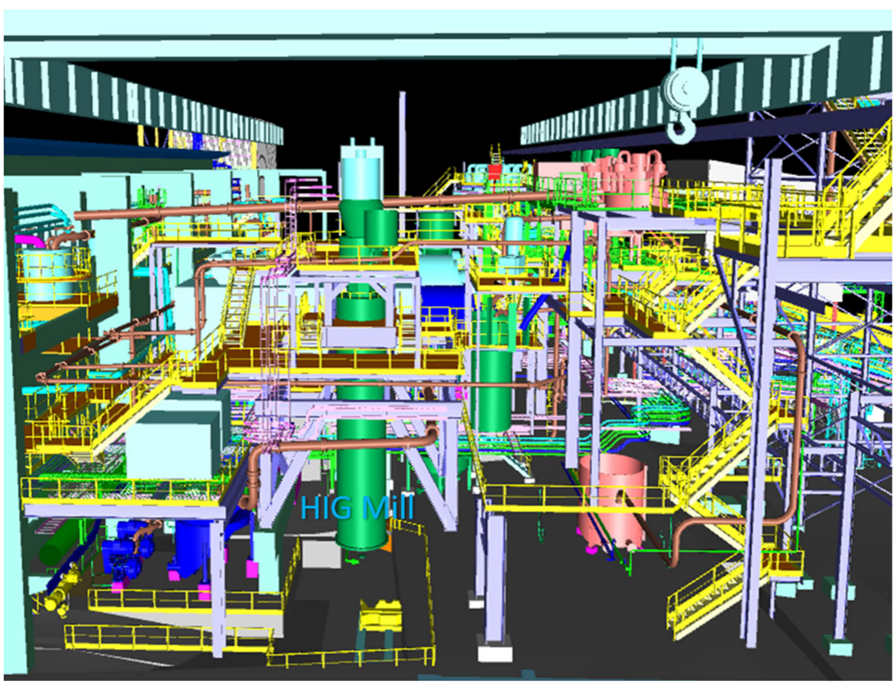

Figure 10—Side view of the HIGmill in position

PROJECT EXECUTION

Table 6 shows the main project schedule for engineering and execution. The HIG mill was commissioned in August 2022, with ramp-up and optimization through to December 2020.

Table 6—Main milestone dates

Major milestones	Date
HIG Mill Order	Sep-19
Delivery	May-20
Order on Local Mechanical Equipment	Jan-20
Order on Structural Steel	Jan-20
Delivery of All Major Equipment	Jun-20
Civil Completion	May-20
Mechanical and EIA Completion	Sep-20
Commissioning Handover	Dec-20

Construction was completed over nine months; commissioning took three months. The project was also executed when the Covid pandemic started, and this complicated the project significantly. The project team executed the project extremely well, with limited resources, and still delivered the project on time.

The capital cost breakdown is shown in Table 7. Imported and local material with spares totaled US$10.6 million. The mechanical, civil, electrical, and control installation contract was for US$1.55 million.

Table 7—Capital cost breakdown

Items	US$ (000s)
Imported Items/Materials	6,693
Local Items/Materials	2,558
Spare Parts	1,360
Transportation	187
Taxes	1,732
Civil Contract	341
Mechanical and EIA Contract	1,213
Other Costs	637
Total Project cost	**14,721**

Thus, the project budget was US$12.7 million; the project eventually was overspent by 18%, mostly due to the delays, logistics, and personnel issues deriving from restrictions due to the Covid pandemic.

As per the schedule, material commissioning started in September 2020 and was completed by October 2020, with handover and ramp-up to December 2020. Mill stability was achieved, and the recovery contribution was observed from September 2020 as the HIGmill was commissioned.

A few challenges were experienced during commissioning, to be expected in a brownfield integration project while the old system is operating. One of the major problems was the feed sump flow characteristics that resulted in material build-up and intermittent surges and blockages. This also prevented the mill from running at stable flow and density. The sump design was adjusted, and the problem was resolved subsequently.

Operational Results

The following sections show the production and wear results.

PRODUCTION RESULTS

The HIGmill achieved stable feed when the feed tank design was changed during Q1 2021. Table 8 and Table 9 show the 2021 and 2022 main operating and cost data. The year's production is divided into operational periods, where the mill had to be stopped for rotor and liner replacement.

The shutdown dates were mostly determined through the mill's grinding performance. When the target grind of 75 µm could not be achieved anymore on maximum speed and torque, the mill was shut down for inspection and component change out. Some of the shutdowns were also due to the stoppage of other major equipment, and this downtime was used to do component change-outs, hence the fluctuation in the operating window durations.

Table 8—2021 operational data

	2021				
	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**
Operation Start Date	Feb-21	Apr-22	May-21	Sep-21	Dec-21
Hours Worked (h)	1,457	566	1,463	1,393	732
Shut Duration (days)	6	4	4	4	5
HIGmill Feed (tonnes)	170,936	69,843	180,666	168,511	78,874
Productivity (t/h)	117	120	125	121	108
SGE (kW/t)	15.41	15.80	15.05	15.81	17.03
Average Power Draw (kW)	2,633,700	1,103,514	2,719,029	2,664,948	1,343,338
P_{80} (PSD)	89	90	91	81	75
Media Consumption (tonnes)	27	11	23	15	11
Consumption (g/kwh)	10.25	10.15	8.59	5.63	8.19
Wear Material (Rotors, Liners, etc.) (US$)	355,370	175,987	332,671	352,781	309,654
Ceramic Media Cost (US$)	85,860	35,618	74,264	47,700	34,980
Electricity Cost (US$)	150,121	62,900	154,985	151,902	76,570
Total Operating Cost (US$)	591,351	274,505	561,920	552,383	421,205
Operating Cost per Tonnes (US$/t)	3.46	3.93	3.11	3.28	5.34

Note: PSD = particle-size distribution; g/kwh = grams per kilowatt hour.

Table 9—2022 operational data

	2022				2023	Total
	Period 6	Period 7	Period 8	Period 9	Period 10	
Operation Start Date	Jan-22	Apr-22	Jun-22	Sep-22	Nov-22	
Hours Worked (h)	1,441	1,356	1,617	1,463	2,117	13,605
Shut Duration (days)	4	4	4	3	3	
HIGmill Feed (tonnes)	156,845	173,086	189,509	187,952	289,066	1,665,290
Productivity (t/h)	111	128	121	124	136	121
SGE (kW/t)	16.78	16.86	16.55	15.03	14.26	15.05
Average Power Draw (kW)	2,631,952	2,917,552	3,137,160	2,824,925	4,122,083	26,098,201
P_{80} (PSD)	80	87	76	76	79	82
Media Consumption (tonnes)	22	21	18	18	29	185
Consumption (g/kwh)	8.36	7.20	5.74	6.37	7.04	7.38
Wear Material (Rotors, Liners, etc.) (US$)	286,688	327,342	624,099	518,414	215,123	3,498,130
Ceramic Media Cost (US$)	69,960	66,780	57,240	57,240	92,220	621,862
Electricity Cost (US$)	150,021	166,300	178,818	161,021	234,959	1,487,597
Total Operating Cost (US$)	506,669	560,423	860,157	736,675	542,302	5,607,589
Operating Cost per Tonnes (US$/t)	3.23	3.24	4.54	3.92	1.88	3.37

Note: PSD = particle-size distribution; g/kwh = grams per kilowatt hour.

The shutdowns were initially high, between six and seven days. This was reduced through the operating years as the team accumulated more experience and confidence. No incidents were ever reported during component change-out, which is attributable to the maintenance team's focus on safety and training. The last shutdown took only three, which was a mine record.

The HIGmill feed rate was also fluctuating in 2021 due to external factors. The mine replaced the two ball mill shells, and the mill operated at times with only one ball mill. During these times the feed was increased to the HIGmill by bypassing some of the Derrick screens, resulting in the full feed fraction to the HIGmill.

The specific grinding energy fluctuated between 14 and 17 kWh/t on average for the periods measured. The grind performance also stabilized well from the second half of 2022. This was achieved through continuous improvement in the feed stability of the HIGmill.

The media consumption varied between 10.2 and 5.7 grams per kilowatt hour (g/kWh). The current media used is 9 mm-diameter Keramos (GMZT38). Caraíba decided to embark on a test campaign to evaluate different media in operations using Kings TA-380. The test was not complete at the time of writing.

Table 10—Technical comparison of the Keramos and Kings media

	Specific Gravity (g/cm^3)	Crushing Load (N)	Vickers Hardness (MPa)
GMZT 3809	3.811	11217	1234.3
King's TA-380	3.728	21507	1322.5

Notes: N = newtons; MPa = megapascal

Figure shows the shaft velocity in revolutions per minute and the torque measurement. The graph shows that the mill is operating most of the time at maximum shaft revolutions and the maximum torque limit. Operating at maximum shaft speed, results in increased component wear. Caraíba embarked on a wear-optimization program. One aspect of this program was to reduce the operational shaft speed. The solution was to install a 3.5 megawatt (MW) motor to replace the existing 2.3 MW motor.

The planned change-out will also be needed for the expansion project to be commissioned in October 2023. The 3.5 MW motor will allow the operation to run at higher media loads, +70%, without exceeding the torque limit. The higher media load and lower speed should give similar or better grinding performance and reduce the liner and rotor wear rate.

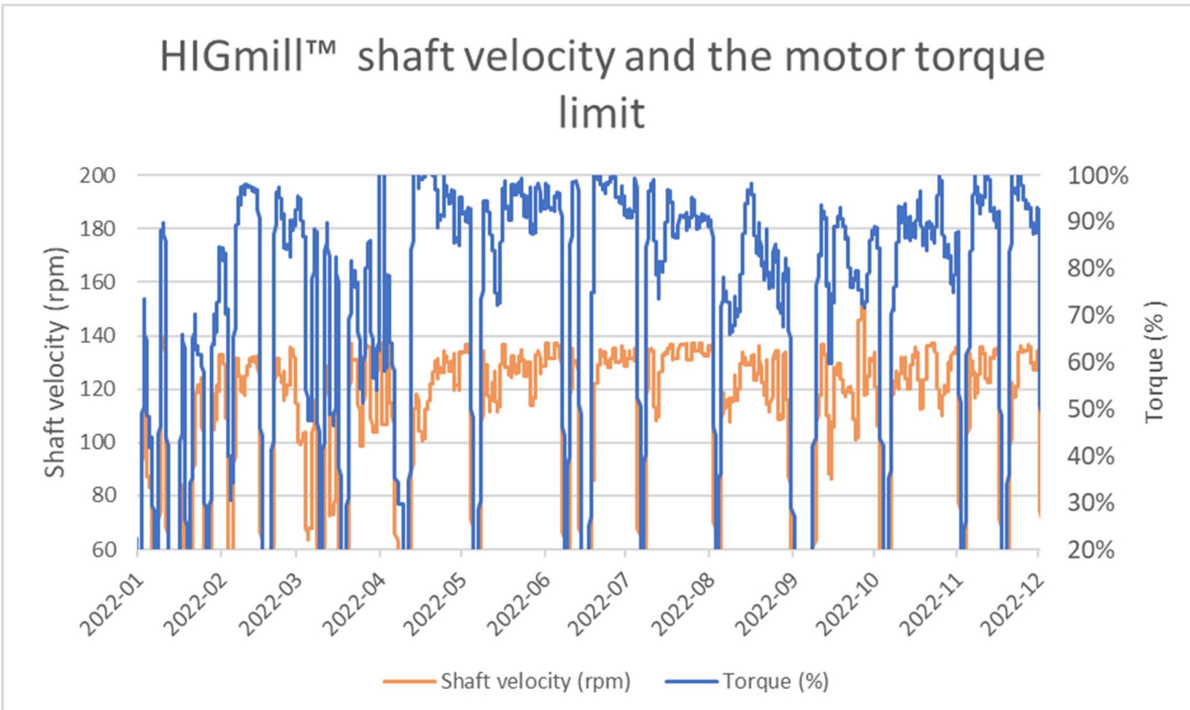

Figure 11—2022 measured hourly torque and shaft velocity data

Table 8 and Table 9 show the operational cost for the wear items. The wear components constituted, on average, 60% of the operating cost over the two-year operation window, at US$2/t treated. The average treatment cost over the two years was US$3.9/t treated.

Figure shows the grade recovery data for 2020 to 2022. The graph shows the increase in recovery at the same feed grades. The graph shows high recoveries in the low feed grades between 0.8% copper and 1.3% copper, specifically. This was a major result for the HIGmill, indicating the liberation capability of the HIGmill at the lower feed grades at Caraíba.

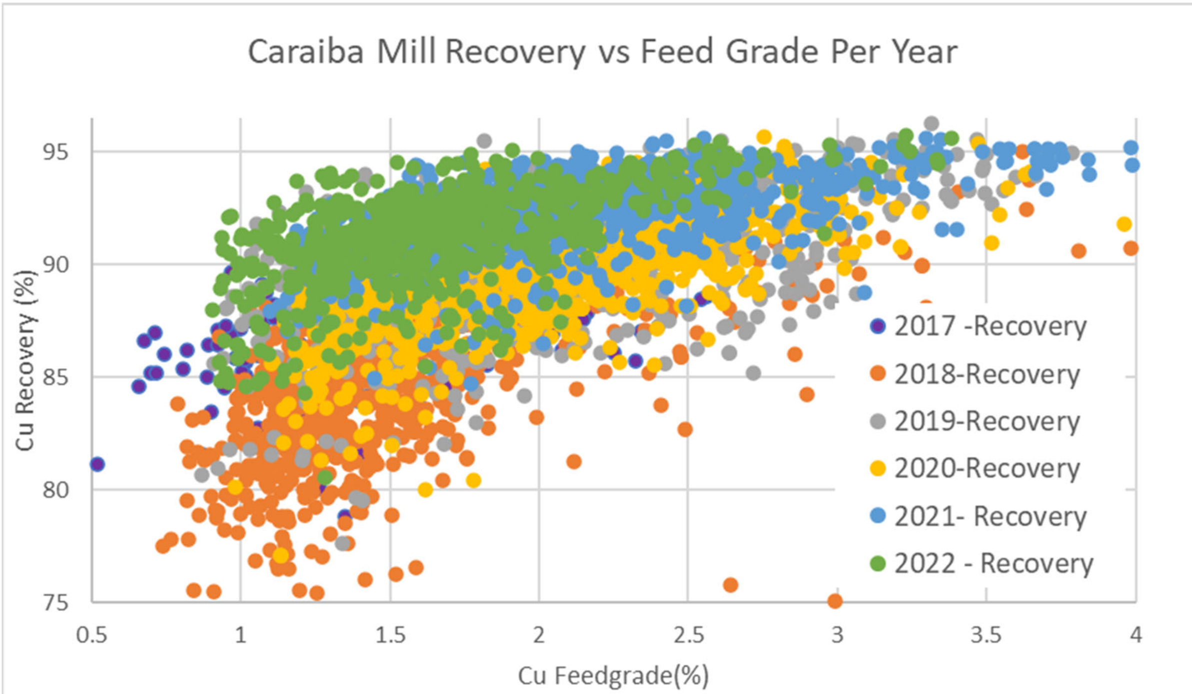

Figure 12—Grade recovery curve data

WEAR RESULTS

The HIGmill was commissioned using Keramos (GMZT38) ceramic beads. The actual media consumption was in line with laboratory tests performed before commissioning. The testing of ceramic beads from five potential suppliers was done at Grinding Solutions in the United Kingdom. The test results conducted on silica sand in a HIG5 laboratory mill ranged from 10 to 16 kWh/t for the five media samples tested.

The average consumption over the two-year operating period considered for the HIG mill at Caraíba was 7.38 g/kWh.

Figure shows the media shape change measured during an operating window. This measurement was performed during each operating window, and Keramos supplied a full analysis of the media performance. The shape change is significant as the media wears down—the smaller media become triangular above 2 mm. This is mainly due to the smaller media being trapped in the voids of the bigger media, which then grinds the surface of the smaller media.

The main liner wear was experienced in the transition zone, where the media level is shown in Figure . The rotor closest to the transition media level accelerates the media into the liner and accelerates wear. Initially, castellated rotors were installed in the transition zone and were later replaced by smooth rotors to minimize the energy in the section. Even with a smooth rotor the operation experienced high wear in the transition zone. The operation is working with the original equipment manufacturer to look at liner construction materials in these areas. The reduction in shaft velocity will also reduce this wear rate.

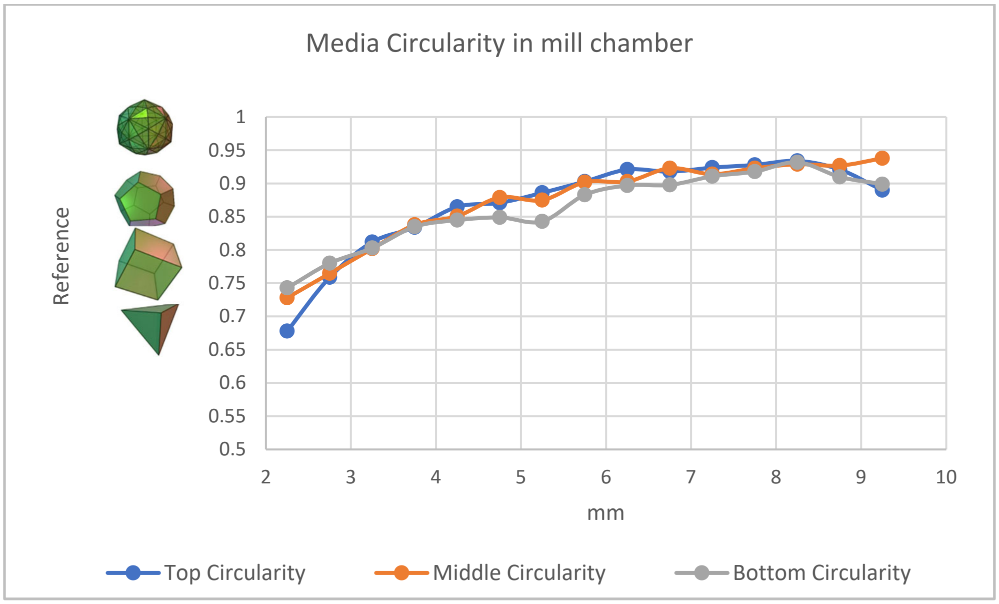

Figure 13—Media shape changes at different particle sizes

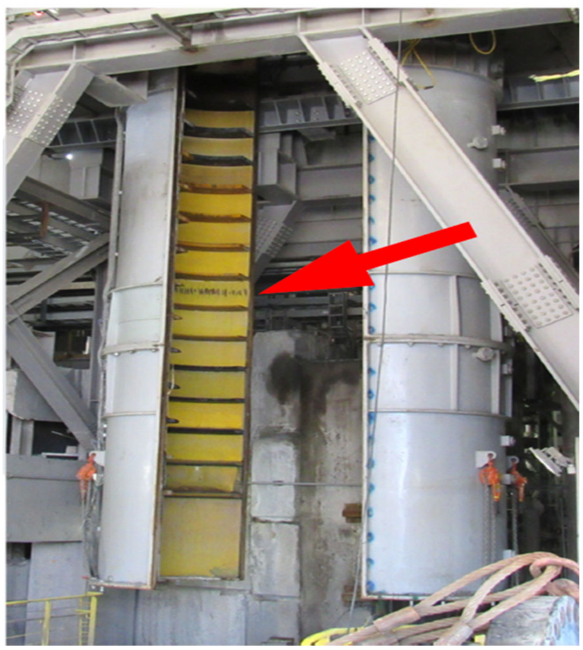

Figure 14—HIGmill liner wear indicated in the mill chamber

The shaft configuration originally selected was a lined shaft bottom cap; with wear-resistant, rubber cranked castellated grinding rotors (GrindForce grinding mechanism) in the grinding media bed; with cranked non-castellated grinding rotors above the media bed.

Figure shows the difference in the shaft configuration selected for commissioning Shaft A) up to Q1 2021, and the current configuration (Shaft B).

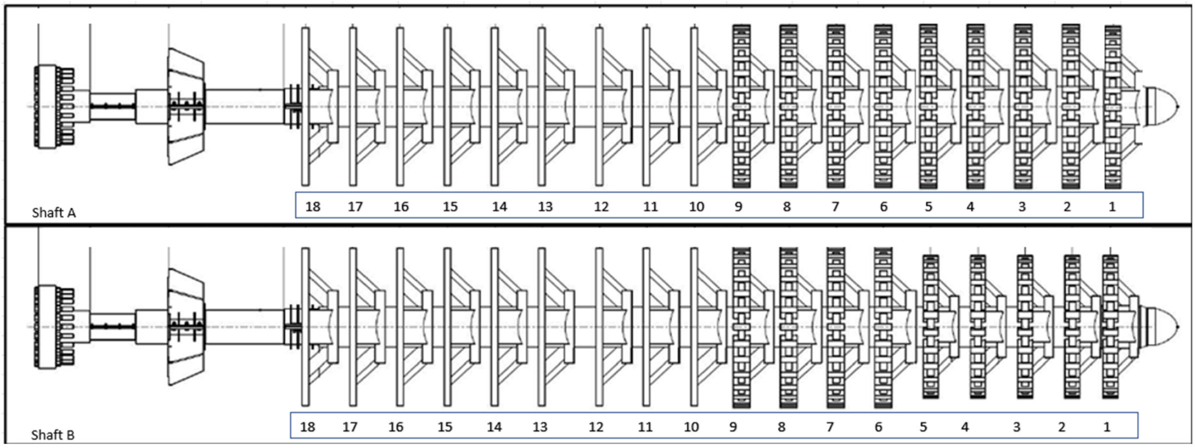

Figure 15—HIGmill shaft configuration changes

Caraíba immediately experienced an increase in rotor life resulting from the change to the Shaft B configuration. The last rotor set installed lasted over 2,000 hours, a significant improvement from the initial 600 hours measured during the earlier operational phases.

HIG Mill Technology Fit with Expansion of Caraíba to 4.2 Mt/a Plant Capacity

The Company's life of mine planning process considers recently completed and ongoing investments in mining and milling infrastructure. Desktop studies were completed in 2019 to evaluate process routes to expand the Caraíba mill. The study used increments, from 3.2 Mt/a to 3.8 Mt/a, then 4.2 Mt/a, and eventually to 5.5 Mt/a. Options considered were:

- Adding a HIGmill - lowering the transfer size to the Ball mills
- Adding a third ball mill
- Adding a second HIGmill or upgrading the HIGmill power to maximum.

Table 11 shows the latest version of the Caraíba mill's five-year plan. The required throughput will be 4.2 Mt/a.

Table 11—Updated 5-year plan for the Caraíba mill

	2023	**2024**	**2025**	**2026**	**2027**	**2028**
Production Capacity (tonnes)	3,383,374	4,202,669	4,200,002	4,200,002	4,200,002	4,212,768
Ore to Plant (blend) (tonnes)	3,188,212	4,201,140	4,200,002	4,200,002	4,200,002	4,212,768
Grade Blend (to Feed at the Plant)(% Copper)	1.54	1.19	1.24	1.25	1.26	1.32
Mass Copper Concentrate (tonnes)	134,614	137,175	143,343	144,739	145,421	153,686
Grade of Copper Concentrate (% copper)	33.5	33.5	33.5	33.5	33.5	33.5
Metal (Concentrate) (tonnes)	45,096	45,954	48,020	48,487	48,716	51,485
Global Recovery (% Copper)	91.7	91.9	92.1	92.1	92.2	92.4

Orway Mineral Consultants (WA) Pty Ltd completed an updated conceptual study in 2021 and 2022. That study included a conceptual trade-off between:

- Adding a high-pressure grinding roll (HPGR) feeding the existing two ball mills
- Adding a third ball mill of similar size and specification as the two existing ball mills.

The trade-off study concluded that the complexity of adding the HPGR into the existing circuit was significantly higher compared to that of installing a third ball mill in an available position in the existing grinding aisle.

The HPGR option was considered, as it simplified the crusher circuit by removing the tertiary crusher stage and had a net energy consumption advantage per ton treated compared to the ball mill circuit.

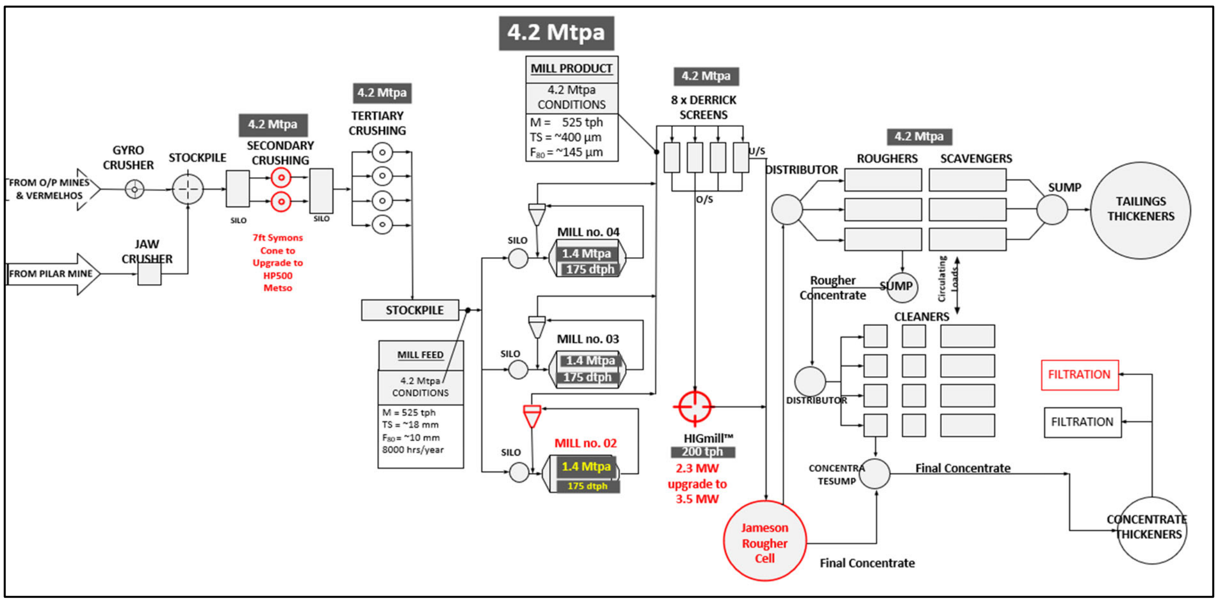

Figure 16—Simplified expansion flowsheet indicating the third ball mill, HIGmill, and Jameson Cell

The existing flotation circuit was surveyed in Q2 2021, and laboratory data were analyzed to calibrate flotation models developed by Orway Mineral Consultants (WA) Pty Ltd. The models indicated retention time limitations when the exiting flotation plant throughput exceeded 3.7 Mt/a. Several options were considered, including:

- Changing the flotation circuit back to the original design with no scavenging capability
- Adding conventional rougher flotation capacity
- Adding a Jameson cell for rougher flotation capacity.

The latter was chosen based on the modularity of the system, ease of integration, and the footprint advantages due to the high unit capacity. It was also thought that there could be metallurgical benefits due to adding different flotation technology with high-intensity slurry and air contact energy, in a hybrid circuit with the current conventional cells.

Pilot testwork at the Caraíba site was concluded in Q1 2022, and rougher Jameson cell recoveries of +80%, and concentrate grades of +33.5% were achieved.

Figure shows the layout model for the third ball mill, HIG mill, and Jameson Cell module. As discussed earlier, the HIG mill will be upgraded with a 3.5 MW motor to accommodate the additional 33% increase in throughput needed for the 4.2 Mt/a. The original HIGmill system was designed and constructed for a 4.2 Mt/a capacity by only increasing the installed power.

In addition to the electrical power increase, an automated media handling system will also be installed. Currently, the manual removal and recharging of the media for shaft inspections and maintenance take nine hours. The control of the media level with the larger motor is also essential for HIGmill performance. The automated system will allow the operators to add media to optimize grinding efficiency levels much more efficiently.

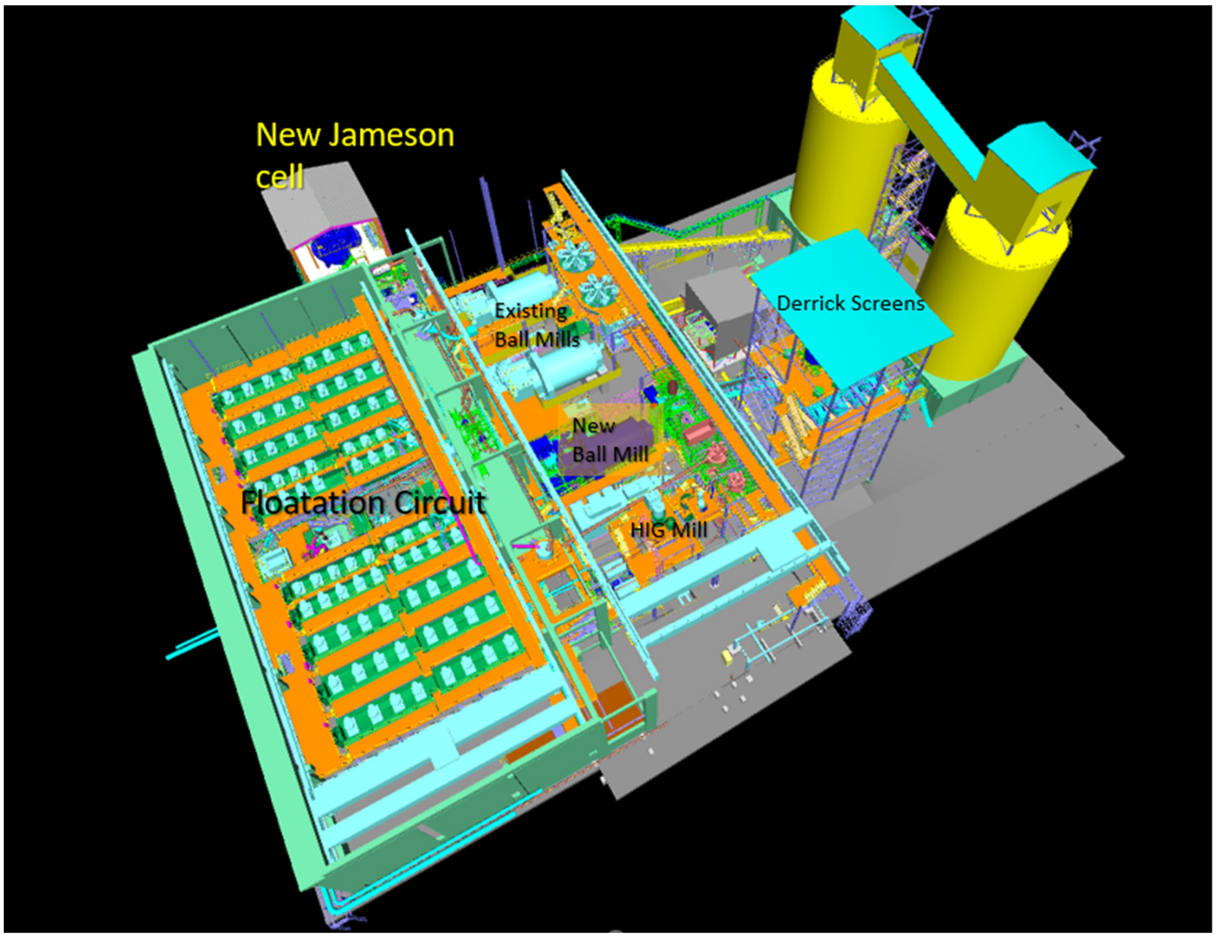

Figure 17—Layout model indicating the HIGmill , third ball mill, and new Jameson Cell module

Conclusions

The metallurgical recovery program that was initiated contributed to the recovery increases since 2018. The initiatives included installing a Carboxymethyl cellulose (CMC) circuit for talc suppression, projects for stabilizing feed grade to the plant, metallurgical accounting system upgrade, and so on. The HIGmill commissioned in the latter part of 2020 started to show its main contribution to metallurgical results beginning at the end of 2022.

As shown in Figure , the year-on-year relationship to the recovery grade curves indicates recovery increases of up to 5% for the same feed grade.

Table 12 shows the recovery profile since 2018, with steady recovery increases in the subsequent years. The typical recovery increases due to the HIGmill were approximately 4% if the recoveries attributed to the other initiatives are excluded.

Table 12—Caraíba mill production data indicating recovery increase.

	Unit	2018	2019	2020	2021	2022
Ore to Plant (blend)	t	2,257,917	2,424,592	2,271,625	2,370,571	2,864,230
Grade	%	1.56	1.93	2.08	2.08	1.76
Mass Copper Concentrate	t	88,179	121,755	127,007	133,865	138,674
Grade of Copper Concentrate	%	34.5	34.76	33.71	34	33.44
Metal (Concentrate)	t	30,426	42,318	42,814	45,511	46,371
Global Recovery	%	86.28	90.5	90.54	92.4	91.93

Assuming an average recovery of 4% and HIGmill average operating cost of US$3.39 per HIGmill ton treated, the capital payback was less than one year.

The data show a significant financial benefit for Ero Copper. The HIGmill technology installed in a fast-track initiative added additional revenue to the company’s bottom line, and the system flexibility introduced allowed for future, simple, circuit upgrades to use the installed HIGmill for the expansion to 4.2 Mt/a. The project was implemented at the peak of the Covid pandemic, and despite this, the project was executed on time and only 18% over budget.

Opportunities to further enhance copper recovery at the expanded tonnages required of the expansion plan have been identified utilizing HIG mill technology. Additional mills treating locked composite copper in the current Derrick Stack Sizer screen undersize, and by regrinding of flotation intermediate concentrates have been identified as possible interventions to optimize liberation and recovery. Further work is in progress.

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