THE COMMINUTION CIRCUIT DESIGN FOR THE CONSTANCIA PROJECT

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ABSTRACT

This paper discusses the process design and layout of the Constancia Project comminution circuit. The circuit consists of a 60 x 113 primary crusher, two 16 MW SAG mills and two 16 MW ball mills. All four mills are twin pinion with wound rotor motor and gearbox drives. Provision for pebble crushing is provided for primary (hypogene) ore treatment later in mine life. The derivation of the mill's specific energy, the equipment selection process and the process used to determine plant throughput for plant design are outlined in the paper. The layout and arrangement of the mills is novel for South and North America

KEYWORDS

Constancia, SAG milling, layout, design

INTRODUCTION

The Constancia deposit is a large-scale porphyry copper orebody located approximately 4100 m above sea level (masl) in the Peruvian Andes about 112 km south of Cusco. The project, that was commissioned in late 2014, was built at a cost of $1.75B and is comprised of an open pit mine, process plant, tailings management facility and supporting infrastructure. The process plant is designed to produce separate copper and molybdenum concentrates.

The project was developed on the following timeline:

- In September 2009, Norsemont Mining Inc announced the positive results of a Definitive Feasibility Study (DFS) completed by GRDMinproc (now part of AMEC) on the Constancia Cu-Mo-Ag deposit.
- In 2010, Norsemont contracted Ausenco to complete and report on a Feasibility Study Optimisation review of the Constancia Project. This culminated in a February 2011 Technical Report that was prepared with input from SRK Consulting Inc and Knight Piésold.
- In 2011, Hudbay Minerals Inc acquired Norsemont and its wholly owned Constancia Project. Ausenco was contracted to provide EPCM services for the plant and associated infrastructure.
- Production began as expected during the fourth quarter of 2014. Commercial production remains on track for the second quarter of 2015 and the mine is expected to achieve full capacity in the second half of the year.

The Constancia property is located in Peru approximately 600 km south-east of Lima. The property sits within the emerging Yauri-Andahuaylas metallogenic belt, hosting several large copper-gold-molybdenum porphyry deposits including Antapaccay (Glencore) and Los Chancas (Grupo Mexico), as well as copper skarn deposits including Tintaya (Glencore) and Las Bambas (MMG). The property is accessed by several roads, and is within 60 km of a railway. Key project criteria are summarised as follows:

- Location: South-eastern Andes of Peru, in the Chamaca and Livitaca Districts, Province of Chumbivilcas, Department of Cusco
- Property: 22,516 hectares in 36 mineral concessions
- Primary metals: copper
- Secondary metals: molybdenum, silver

- Mining method: open pit
- Daily ore throughput: 80k t/d when treating softer supergene ore
- Average annual Cu production: 82k tonne
- Mine life: 22 years

The Constancia concentrator contains a comminution circuit that reduces the ore to an 80% passing size of 106 microns. This paper describes the:

- derivation of the grinding mill's specific energy
- the equipment selection process
- the process used to determine plant throughput
- plant layout options and comparisons
- early start-up experiences.

CIRCUIT SELECTION

Description of Ore Characteristics

The metallurgical testwork programs for the feasibility study were managed by Lima-based Transmin Metallurgical Consultants. Testwork programs were conducted by C.H. Plenge Laboratory in Lima and SGS Minerals Chile. The comminution testwork data is appended and summarised in Figure 1. The relationship between ore competency, as measured by the Drop Weight index (DWi), and ore hardness as measured by the Bond ball mill work index is reasonably consistent with the main outliers being mixed ore samples. The 75th percentile values for each ore type were used in the absence of any other relationship linking ore properties to the block model.

Ore processed in the initial years of plant operation is a combination of mixed and supergene ores that are both low competency and soft, requiring substantially less comminution energy than later hypogene ore treatment.

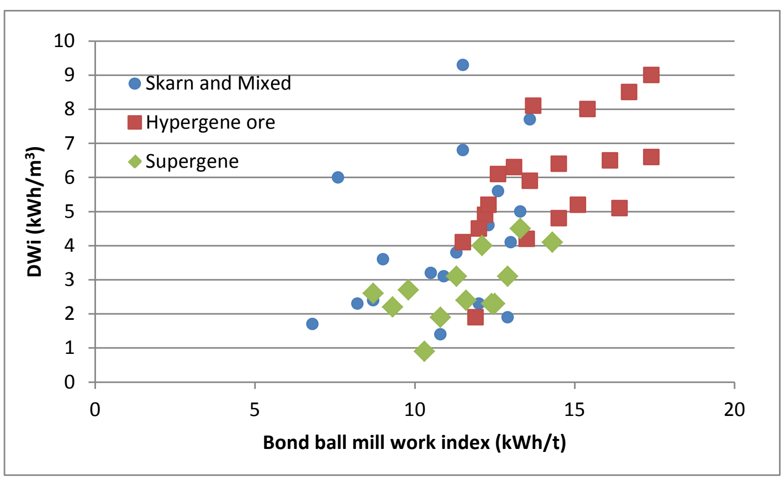

Figure 1 - Relationship between Bond ball mill work index and SMC DropWeight Index (DWi)

The DWi values are related to the Axb values by:

$$\mathrm{DWi} = \mathrm{c}/(\mathrm{SG}.(\mathrm{Axb})^\wedge\mathrm{z}), \text{where c and z are constants.}$$

The Axb parameters, which were used to determine SAG mill throughput, are inversely related to the core competency. That is, the lower the value, the more competent the ore and the lower the throughput for a given SAG mill geometry and operating condition.

The Bond ball mill work index (BWI) data were used to determine the ball mill power requirement. Table 1 summarises the 75th percentile values for the various comminution parameters used to determine plant throughput and mill power draw. A more complete list of comminution data is provided in Appendix 1.

Table 1 - Calculated 75th percentile ore characteristics

Ore Type	**Axb**		**BWI**	**S.G.**	**DWi**
Units	75th percentile	50th percentile	75th percentile (kWh/t)	75th percentile (t/m^3)	75th percentile (kWh/m^3)
Hypogene	38	42.5	15.9	2.54	7.3
Supergene	77	90	12.8	2.47	3.7
Skarn	76	120	11.5	3.73	3.8

Initial Optimisation Studies

A review was completed in 2010 of the DFS mine plan, flow sheet and equipment selection that concluded that there were opportunities to substantially improve the throughput of the concentrator comminution circuit for a relatively small increase in capital cost. A number of alternatives that added value to the project business case were identified. They included increasing throughput and grinding circuit installed power to maximise net present value. The use of a dual SAG mill arrangement in a cost effective layout added substantial value to the project by increasing both initial and post Year 6 plant throughput for a modest increase in project capital cost when compared with the DFS case of a single 21.5 MW Gearless Motor Drive (GMD) SAG mill.

The mine planning and scheduling process required estimates of plant throughput based on ore type. Plant throughput is typically limited by ore competency with a secondary limitation due to the optimum P80 and related flotation recovery. Flotation recovery losses were estimated in the feasibility study to be about 2% per root 2 aperture screen size increase (e.g. 106 µm to 150 µm) for supergene ore and substantially greater for hypogene ore. However, reinterpretation of testwork and additional testing indicated that the sensitivity of rougher recovery to grind size was lower for hypogene ore than indicated in the DFS test work.

A number of scenarios were modelled to determine throughput and mill pinion power. These scenarios considered SABC circuits and SAB circuits, preceded by secondary crushing when treating competent rock, with a single grinding train using 20 to 26 MW GMD driven SAG mills and dual grinding trains using 13 to 16 MW twin pinion gear driven mills.

Singe train GMD driven options were discarded early in the assessment in favour of a dual train pinion driven SAG mills due to the added flexibility, reduced start up risk and the increased total SAG mill power available.

Table 2 summarises the criteria used for plant assessment.

Table 2 - Assumed production schedule inputs

Availability	91.3%
Hours per day	24
Target grind size (P80 µm)	106
Target throughput – hypogene ore (t/h)	3167

The Feasibility Optimisation Study resulted in the selection of a dual train grinding circuit with each train comprised of a 16 MW SAG mill and a 16 MW ball mill. All mill drives were dual pinion with the SAG mill speed controlled by slip energy recovery systems.

DERIVATION OF THE PLANT THROUGHPUT

Specific Energy Determination

The specific energies of the SAG and ball mills were determined using AusGrind (Ausenco's in-house software) (Lane, Foggiatto, Bueno and McLean, 2013) and Morrell's method. SAG mill specific energy was a function of the inverse of the Axb value, the mill geometry and the mill operating conditions. Ball mill specific energy was calculated using a variation of Bond's formula for total specific energy and subtracting the SAG mill specific energy.

Block Model Inputs

Table 3 summarises the maximum plant throughput based on the 75th percentile ore competency (Axb value) and ore hardness (Bond ball mill work index), including allowances for plant ramp up.

Table 1 - Estimates of Maximum Plant Capacity

Ore Type	**Maximum Mining Rate, t/h**				
Year	**0.5**	**1**	**2**	**4 to 6**	**7**
100% Hypogene	2000	2300	2550	2550	3000
100% Supergene	2500	2850	3167	3167	3167
100% Skarn	2500	2850	3167	3000	3167

When supergenes (and early skarn ores) are blended with hypogene ores the plant throughput for Years 1 to 6 was predicted by:

$$\text{Max plant throughput} = -23.62 \times (\%\ \text{hypogene ore}) + 4341$$

All solutions of the above equation for less than 50% hypogene (per the DFS mine schedule to Year 6) give values greater than 3167 t/h (76 000 t/d) per Figure 3.

When pebble crushing is operating:

$$\text{Max plant throughput} = -8.54 \times (\%\ \text{hypogene \& skarn ore}) + 3838$$

When pebble crushing is not operating (pre Year 7):
Max plant throughput =0.85 x (-8.54 x (% hypogene & skarn ore) + 3838)

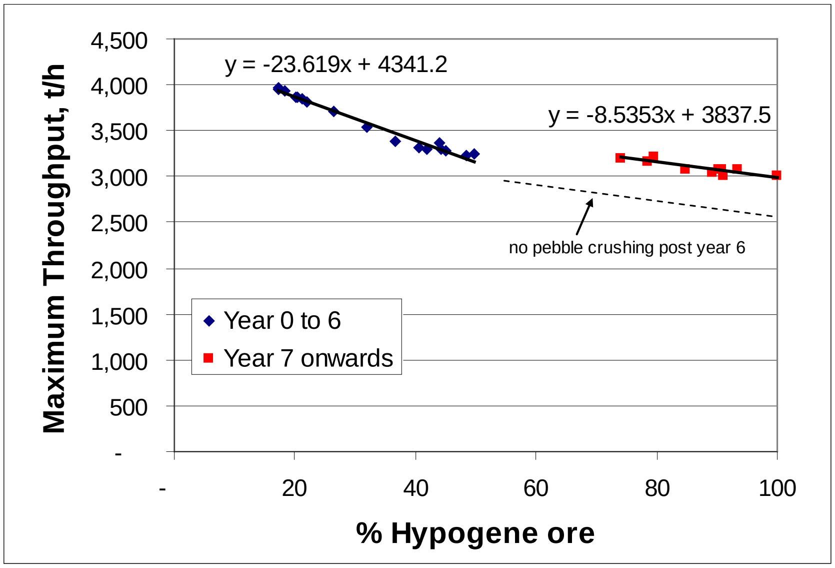

Figure 2 - Plant capacity model as a function of ore type

The twin 16 MW SAG mills and twin 16 MW ball mills with the installation of the pebble crusher deferred to Year 6 resulted in:

- SAG mill throughputs maintained at 3170 t/h for the initial 6 years without pebble crushing
- The ball mills were potentially slightly overloaded after Year 6 producing a P80 of between 120 and 130 microns compared with the target P80 of 106 microns. The value of the increase in throughput more than countered the loss of recovery due to the coarser P80.

Effect of Ore Characteristics and Core Geotechnical Data on Primary Crusher P80

Ausenco's crusher models rely on the Axb parameter to predict the P80 from the primary crusher. The ROM ore size distribution is a function of the geotechnical properties (fracture frequency and Rock Quality Designation (RQD)). Hence, the feed size to the SAG mill is a function of rock competency (Axb) and rock fracture.

Burger, McCaffery, McGaffin, Jankovic, Valery, & La Rosa (2006) and Wirfiyata and McCaffery (2011) reported that Batu Hijau has an average Axb of 39 (range typically 35 to 65), an average Bond ball mill work index 11.4 kWh/t and an average RQD of 44%. RQD values of 25% resulted in a SAG mill feed size (F80) between 55 and 60 mm and throughputs of 6200 t/h. RQD values of 55% resulted in SAG mill feed size (F80) of over 70 mm and a SAG mill throughput of 5200 t/h. The Batu Hijau SAG mill specific energy was a function of point load test and RQD. The point load test substitutes for Axb measurement in that relationship.

The Batu Hijau ore is less fractured than the Constancia ore based on the average RQD data and Constancia's SAG mill F80 is likely to be less than 70 mm. The average RQD for the Constancia comminution hypogene samples was less than 20%. As a result, Ausenco's standard model was adjusted to reflect a lower, but conservative, primary crusher P80 of 70 mm for hypogene ore compared with the standard model prediction of 95 mm (without consideration of the RQD data). This had the effect of reducing the SAG mill specific energy by 10% and increasing the maximum SAG mill throughput by 10%

The SAG feed F80 for the skarn and supergene ores was already significantly finer than a P80 of 70 mm due to the high Axb values.

Verification Using JKSimMet

Transmin ran JKSimMet simulations (Table 4 and Figure 3) to validate the Ausenco method. The new feed F80 was fixed at 115 mm for simulation purposes, per the JKTech methodology reported by Morrell and Robinson (1996) using the ta, DWi and the close side setting of primary crusher.

Table 4 - Summary of simulation parameters

Parameter	Units	AusGrind	JK SimMet
Hypogene Throughput	t/h	3400	3468
F80	mm	95	115
SAG Mill	no x diam x length	2 x 36' x 24'	2 x 36' x 24'
SAG Mill Power (installed)	kW nameplate	32,000	32,000
SAG Specific Energy	kWh/t	8.14	9.14
Ball Mills	no x diam x length	2 x 26' x 40.5'	2 x 26' x 40.5'
Ball Mill Power (installed)	kW nameplate	32,000	32,000
Ball Mill Specific Energy	kWh/t	9.28	8.66

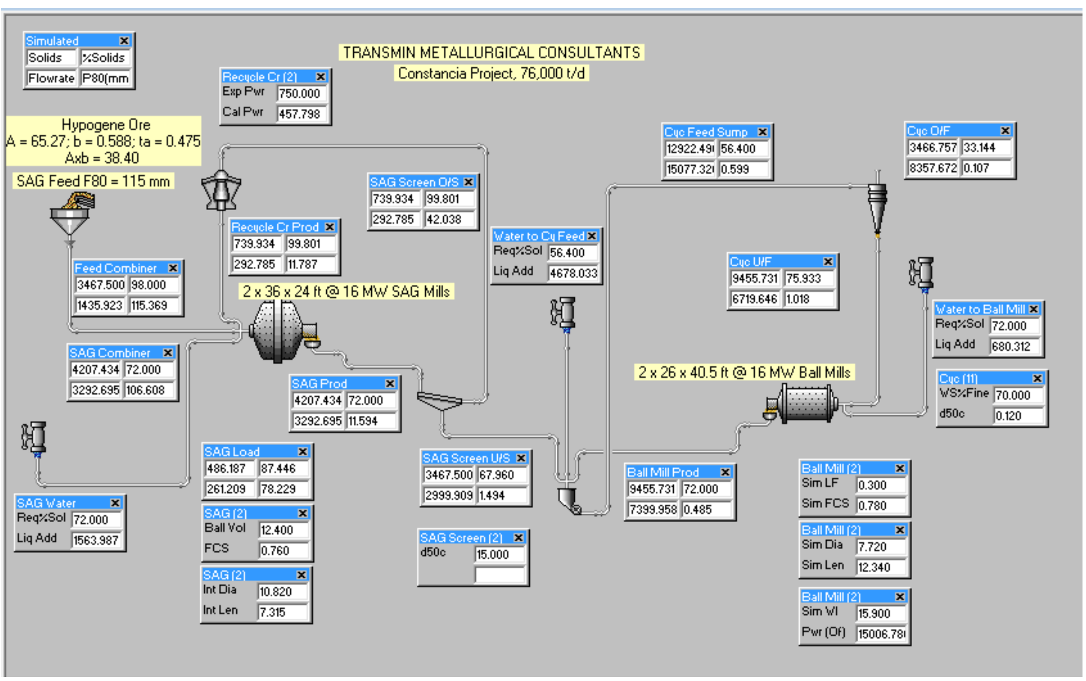

Figure 3 - JKSimMet outcome

EQUIPMENT SELECTION PROCESS

The selection of comminution equipment flowed from the determination of mill specific energy requirements. The major considerations are listed below.

Primary Crusher

The choice of primary crusher was between a 60 x 89 and a 60 x 113. The final selection of a 60 x 113 was based on de-risking the plant for the treatment of competent primary ore. Whilst the 60 x 89 crusher had the volumetric capacity, the SAG mill throughput is sensitive to crusher product size distribution and a target OSS of 150 mm on competent ore would lead to power requirements above 600 kW. Hence, the larger 60 x 113 crusher with 1,000 kW motor was selected.

Mill Drive Type

Given that about 32 MW each of SAG mill and ball mill power was required, the use of a GMD SAG mill at an altitude above 4000 m would have required one or a combination of the following:

- A reduction in SAG mill power to say 28 MW (per Toromocho and Minas Conga)
- A reduction in maximum throughput capacity
- Moving from a SABC circuit to a SACB circuit (with crushed pebbles to ball mill feed),
- The potential use of secondary crushing after Year 6, or
- High intensity blasting in the mine.

The geared drive mills are lower capital cost but the requirement for two reclaim tunnels and SAG mill feed systems removes some of the capital savings (Table 5). Although the testing and pre-commissioning process for a GMD mill is more costly and takes longer than an single geared mill (by about 10 weeks), this process is on a par with dual geared mills.

Table 5 - Comparison of the capital cost of gearless and geared SAG mill drives and reclaim systems

Area	GMD System	Geared System
SAG mill and motor cost (US$/MW)	39	32
Installed cost (USM	61	50
Cost of reclaim and SAG feed system (US$M)	15	20
Approx. total cost (US$M)	76	70

Given the extensive maintenance issues with GMD mills in the five years prior to 2011, and the following advantages of the geared mills led to the selection of the twin line geared system:

- De-risking of plant start-up issues using twin milling trains
- Higher installed SAG mill power for maximum plant throughput
- Less complex systems for maintenance
- Reduced requirement for weather protection
- Lower or equivalent capital cost

The optimum design had a slight bias towards more power on the ball mills than for the SAG mills, but 16 MW mills were selected for the SAG and ball mills, thus standardizing the motors to the same 8 MW model that would facilitate spares and interchange ability to reduce working capital and risk (Table 6).

Table 6 - Summary of major comminution equipment criteria (primary hypogene ore)

Facility	Criteria	Units	FS Design	Design As Built
Primary crusher	Crusher type		Gyratory	Gyratory
	Size	inches	60 x 89	60 x 113
	Installed power	kW	600	1000
Pebble Crushers	Duty		SAG mill pebbles	Deferred to year 5
	No of crushers		2	
	Installed power	kW	820	
SAG Mill	No of mills		1	2
	Mill diameter	inside shell (m)	11.58	10.97
	Mill EGL	inside liner and grate (m)	7.90	7.31
	Drive type		GMD	Twin pinion
	Mill speed	% critical	0-82	65-80
	Installed power	MW (per mill)	21.5	16
Ball Mills	No of mills		2	2
	Mill diameter	inside shell (m)	7.32	7.92
	Mill EGL	inside liner (m)	12.2	12.34
	Drive type		Twin pinion	Twin pinion
	Mill speed	% critical	75 (fixed)	78 (fixed)
	Installed power	MW (per mill)	13	16
	P80 (hypogene)	Micron	106	106

PLANT LAYOUT OPTIONS AND COMPARISON

Feasibility Study Layout

The feasibility study site layout is presented in Figure 4. The primary crusher was set into an elevated position across a small valley from the crushed ore stockpile. Reclaimed ore is conveyed along a relatively flat spur to the SAG mill. The SAG mill and ball mill were arranged in an end to end arrangement, consistent with most north and South American concentrators (Figure 5).

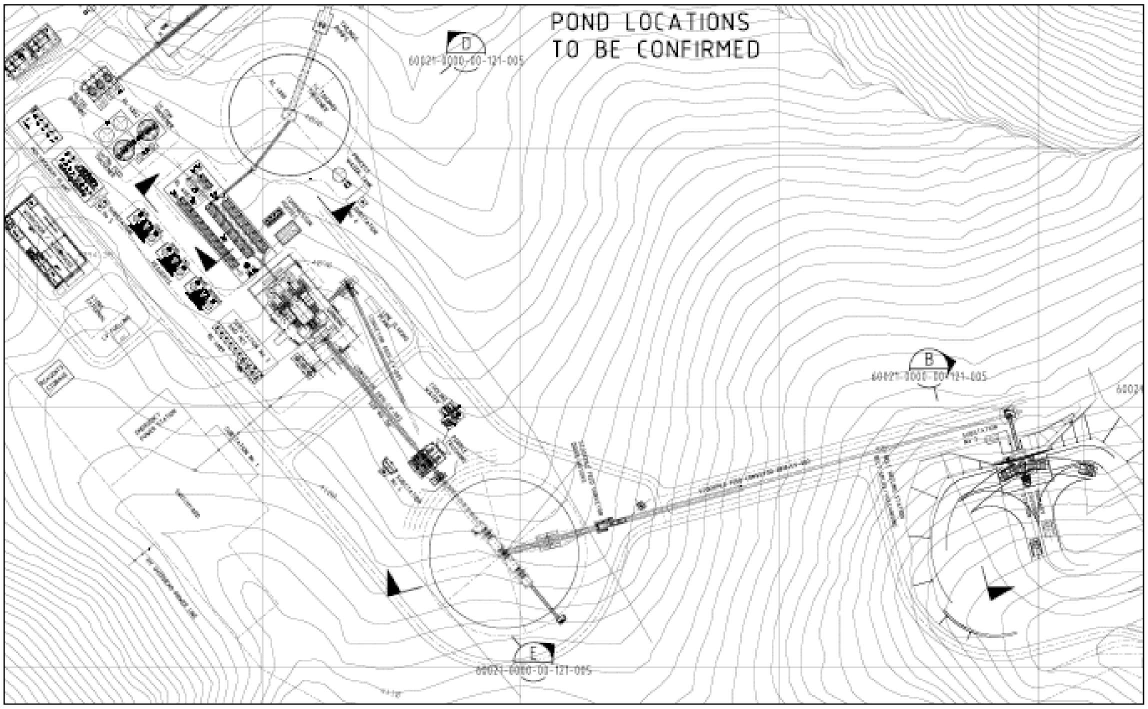

Figure 4 - Feasibility study site layout

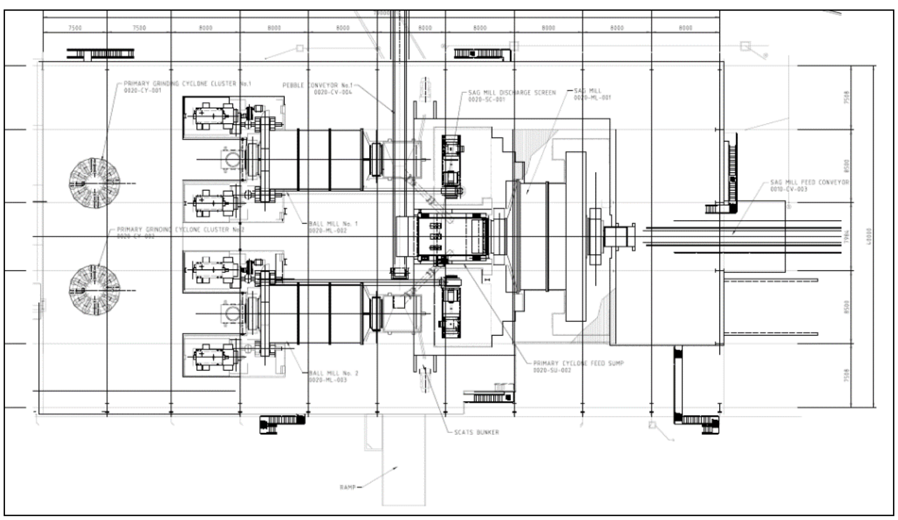

Figure 5 - Feasibility study grinding circuit plan

Final Optimised Layout

The final optimised layout comprised dual grinding lines consisting of two parallel reclaim tunnels, each with two reclaim apron feeders and SAG mill feed conveyors feeding two lines of opposed SAG and ball mills (Figures 6 to 8). The SAG mill feed conveyors are perpendicular to the axis of the SAG mills. This is unusual in North and South America, but relatively common practice in Australia.

The grinding reline floor (which is common for all 4 mills) is accessed by a ramp from the bank near the workshops. E-rooms are all adjacent to each other are located under the grinding floor and lube rooms are under the floor adjacent to each mill. Cyclone maintenance and ball mill ball addition is via a portal crane above the central corridor between the milling lines. The cyclone underflow has a branch to allow a portion of the underflow stream to report to the SAG mill feed chute; the remaining underflow stream reports to the ball mill.

Trommels were chosen over screen decks on the mill discharges, reducing the height required between the mills and the pump box.

Pebbles from the SAG mills are recycled via transfer conveyors and allowance is made for the retrofitting of pebble crushers for the treatment of more competent primary hypogene ore later in mine life.

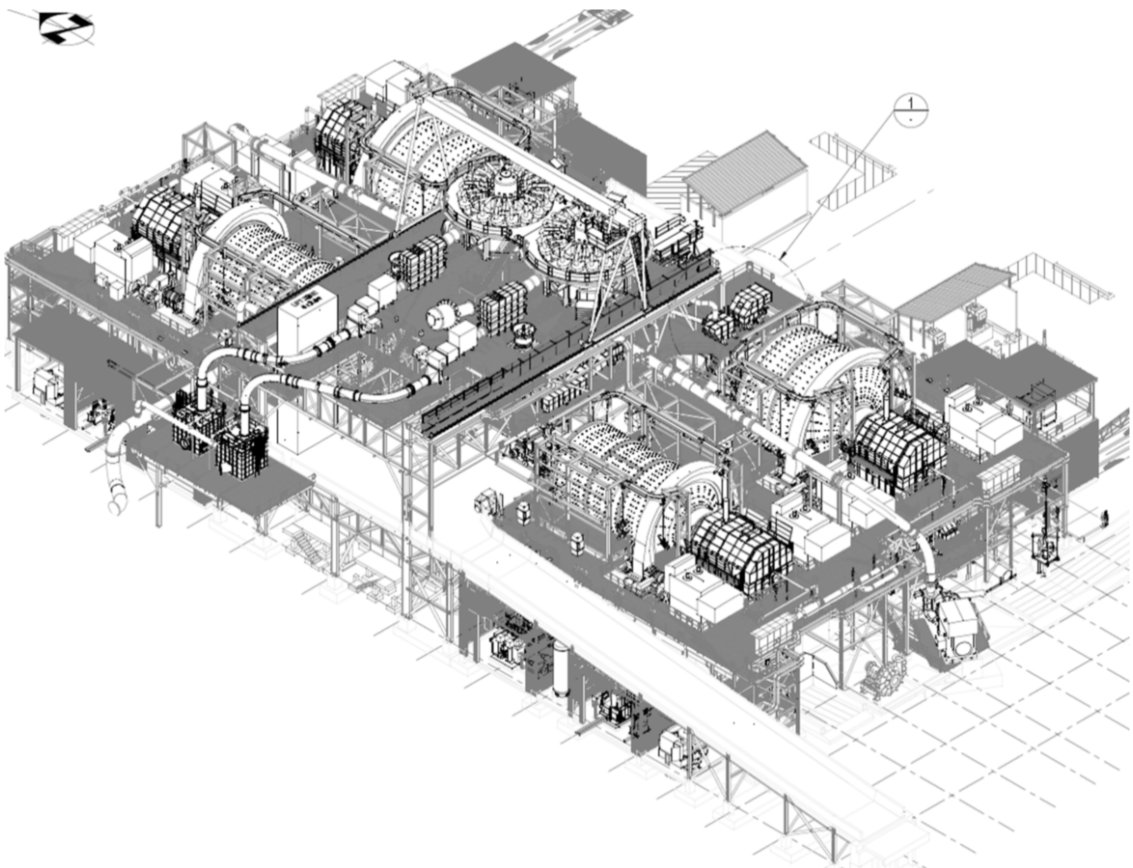

Figure 6 - Constancia dual line grinding circuit

Figure 7 - Constancia grinding circuit viewed from the primary crusher

Figure 8 - Grinding floor between grinding lines

Layout Comparison

The final layout was optimised to minimise bulk material quantities and costs whilst still retaining good operability and maintainability. This was achieved by:

- Optimising plant footprint and height of structures
- Not installing the mills in a covered building
- Use of mobile cranes for periodic mill maintenance
- Use of gear driven mills

The final optimised layout of the Constancia grinding circuit used approximately 14 000 m^3 concrete and 1300 t steel for 64 MW of installed power. This compares with 14100 m^3 concrete and 630 t of steel in the original DFS for 47.5 MW of installed power. The improvements in concrete quantities per MW of installed power were a function of the improved and more cost effective layout. Some of the steel increase is associated with the structure required for the dual line SAG mill feed conveyors, the remainder is pro-rata for the increase in mill power.

PROJECT START-UP

The Constancia grinding circuit commenced ore commissioning on Line 2 on 16 Dec 2014 with the operation of Line 1 commencing on 1 Feb 2015. Ramp up to design capacity on an hourly throughput basis was achieved with very low ball load due to the soft nature of the mixed ore used for commissioning. Figure 9 illustrates the ramp up to full production from commencement of Line 1 start-up. Prior to this, Line 2 operated at 20 to 30 kt/d until an outage associated with control system and bearing issues.

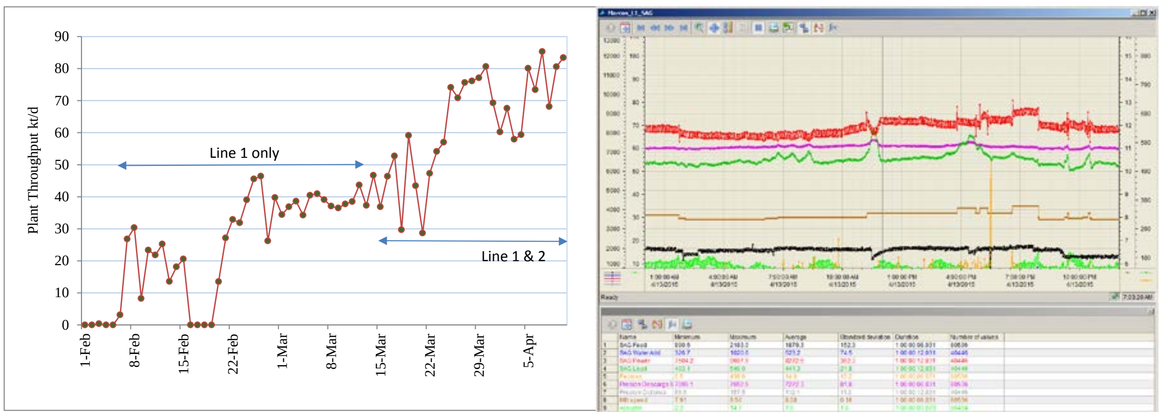

Figure 9 - Ramp-up in Throughput from Line 1 Commencement and a Typical SAG Mill Operating Trend When Treating the Softer Mixed Ore

Key commissioning milestones are listed below:

- 24 October 2014 – First ore crushed to stockpile. Crushing with haul trucks commenced a day later.
- 16 December 2014 – First ore milled in Line 2 grinding circuit.
- 22 December 2014 – First continuous operation of Line 2 grinding circuit
- 27 December 2014 – First copper concentrate filtered and discharged using Line 2 roughers and three stage cleaner circuits, no regrind.
- January 2015 – Line 2 operating at between 800 and 1800 t/h. Issues with grate blockage hindering slurry flow from SAG mills and reducing power draw and throughput.
- 24 January 2015 – Line 2 grinding mills outage and bearing damage.
- 1 February 2015 – First ore milled in Line 1 grinding circuit.
- February 2015 – Line 1 running at throughputs as high as 2100 t/h for a shift. Ore very soft and issues with grate blockage hindering slurry flow from SAG mills and reducing power draw and throughput.
- 16 March 2015, Line 2 resumed operations.
- 29 March 2015, achieved design throughput for three consecutive days.

CONCLUSION

The Constancia Project grinding circuit represents a departure from typical large North and South American grinding circuit design norms. The 16 MW twin pinion wound rotor drives and the opposed mill layout represent a compact and cost effective solution for a high capacity copper concentrator at 4100 m elevation in the Peruvian Andes. The eight 8 MW motors and the mill drive systems share common components that mitigates risk in operation and maintenance, and reduces the cost of major spares holdings for Hudbay.

The mill selection process was done using Ausenco's Ausgrind software and checked by Transmin using JKSimmet. Due cognisance was taken of the rock quality when determining the relationship between the benchscale test work data and the SAG mill specific energy to determine throughput.

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Appendix 1 – Commution Characteristics

Composite	LithoType	BWI (kWh/t)	S.G. (t/m^3)	Ai, g	SMC Dwi (kWh/m^3)	SMC Axb	JKDWT A*b	SPI, (min)	RQD %
PHY	HY	15.8	2.75	0.17	-	-	-	75	
M-12	HY	13.1	2.45	0.29	6.30	39	-	-	
M-13	HY	13.7	2.57	0.18	8.10	32	-	-	29
M-14	HY	14.5	2.48	0.25	6.40	39	-	-	3
M-15	HY	15.4	2.50	0.29	8.00	32	-	-	8
M-17	HY	12.2	2.47	0.17	4.90	51	-	-	0
M-18	HY	11.9	2.28	0.02	1.90	121	-	-	19
M-22	HY	16.1	2.50	0.16	6.50	39	-	-	
M-23	HY	17.4	2.56	0.20	9.00	28	-	-	12
M-24	HY	16.4	2.39	0.18	5.10	47	-	-	0
M-25	HY	15.1	2.57	0.18	5.20	49	-	-	49
M-26	HY	11.5	2.43	0.11	4.10	59	-	-	
M-27	HY	13.6	2.48	0.24	5.90	43	-	-	
M-28	HY	12.6	2.40	0.13	6.10	39	-	-	15
M-29	HY	16.7	2.50	0.29	8.50	29	-	-	
M-32	HY	14.5	2.57	0.10	4.80	54	-	-	
M-37	HY	12.0	2.44	0.25	4.50	54	-	-	
M-38	HY	13.5	2.44	0.13	4.20	58	-	-	0
M-39	HY	12.3	2.59	0.10	5.20	50	-	-	3
M-42	HY	17.4	2.52	0.27	6.60	38	-	-	
HY*	HY	13.4	2.43	0.10	-	-	68.6	42.9	
M-10	MX	11.3	2.46	0.23	3.80	66	-	-	
M-11	MX	12.0	2.33	0.08	2.30	100	-	-	
M-19	MX	13.6	2.44	0.18	7.70	31	-	-	
M-20	MX	13.3	2.44	0.17	5.00	49	-	-	
M-35	MX	12.3	2.47	0.14	4.60	54	-	-	
M-36	MX	12.6	2.44	0.13	5.60	43	-	-	
M-40	MX	13.0	2.43	0.15	4.10	60	-	-	
PSG	SG	12.9	2.75	0.12	-	-	-	39.8	
M-1	SG	13.3	2.50	0.14	4.50	56	-	-	
M-2	SG	9.3	2.36	0.09	2.20	108	-	-	
M-3	SG	12.5	2.41	0.06	2.30	104	-	-	
M-4	SG	11.3	2.38	0.11	3.10	77	-	-	
M-5	SG	14.3	2.36	0.10	4.10	58	-	-	
M-6	SG	11.6	2.20	0.07	2.40	92	-	-	
M-7	SG	8.7	2.47	0.26	2.60	95	-	-	
M-8	SG	12.9	2.47	0.09	3.10	80	-	-	

Composite	LithoType	BWI (kWh/t)	S.G. (t/m3)	Ai, g	SMC Dwi (kWh/m3)	SMC Axb	JKDWT A*b	SPI, (min)	RQD %
M-9	SG	12.1	2.36	0.11	4.00	60	-	-	
M-16	SG	12.4	2.37	0.15	2.30	102	-	-	
M-21	SG	10.3	2.27	0.03	0.90	247	-	-	
M-33	SG	10.8	2.49	0.13	1.90	133	-	-	
M-34	SG	9.8	2.43	0.16	2.70	92	-	-	
SG*	SG	12.7	2.45	0.08	-	-	82.2	43.8	
PSK	SK	11.2	3.66	0.09	-	-	-	64.5	
M-30	SK	6.8	4.18	0.03	1.70	245	-	-	
M-31	SK	10.8	3.18	0.03	1.40	232	-	-	
M-41	SK	10.9	4.16	0.10	3.10	133	-	-	
M-43	SK	9.0	3.51	0.03	3.60	97	-	-	
M-44	SK	10.5	2.73	0.02	3.20	86	-	-	
M-45	SK	11.5	3.56	0.05	9.30	39	-	-	
M-46	SK	12.9	2.67	0.05	1.90	140	-	-	
M-47	SK	8.2	2.77	0.25	2.30	121	-	-	
M-48	SK	11.5	3.08	0.09	6.80	45	-	-	
M-49	SK	8.7	2.85	0.05	2.40	119	-	-	
M-50	SK	7.6	3.90	0.02	6.00	65	-	-	
SK*	SK	12.7	2.6	0.06	-	-	124	49.8	