Mount Carlton comminution circuit design, start-up and optimisation

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ABSTRACT

The Mount Carlton project in Queensland's North East sits on a high-sulphidation epithermal style deposit rich in gold, copper and silver.

Mt Carlton is an open pit mining operation with ore processed using a primary crusher, single stage SAG mill and flotation to produce a concentrate for sale. Orway Mineral Consultants (OMC) was involved in the original design of the comminution circuit and the project was commissioned in late 2012, with first concentrate shipped in March 2013. When Evolution sought to optimise the project in 2015, OMC was invited to assist by undertaking a circuit review to identify opportunities for the optimisation.

During 2016, the Mt Carlton site team implemented the optimisation strategies developed in conjunction with OMC. These included reconfiguring the SAG mill discharge arrangement, reducing the average ball diameter and allowing the mill to operate at higher speed and under more autogenous conditions. Cyclone operation was changed to constant pressure and the vortex finder size was decreased.

The combined strategies improved energy efficiency and allowed higher SAG mill power utilisation. The additional power has been used to increase throughput by 2.4 per cent while achieving a 27µm reduction in product size (P_{80}) to gain downstream recovery improvements. The reduction in grind size has been achieved with only 6.8 per cent increase in specific energy consumption because of a 6.5 per cent increase in grinding efficiency. The circuit product size is also notably more consistent due to the improvements made to the cyclones, providing benefit to the downstream flotation circuit. A significant decrease in ball consumption was also gained, saving hundreds of thousands of dollars a year in operating cost.

This paper will discuss the circuit design, start up and will detail the changes made during the optimisation and why these were successful.

INTRODUCTION

The Mt Carlton Gold-Silver-Copper project is owned by Evolution Mining and is located in the Central North of Queensland (Figure 1).

The project was discovered in 2006 and commissioned in December 2012 with first concentrate produced in March 2013. This paper looks at some of the decision making during the design of the primary crushing-single stage SAG (SS SAG) circuit with recycle crushers, the performance post commissioning and following optimisation.

Figure 1 – Location of Mt Carlton.

GEOLOGY

The Mt Carlton project is a high-sulphidation epithermal style deposit with mineralisation occurring within felsic volcanic rocks on the northern margin of the Permian Bowen Basin. The project comprises gold, silver and copper primarily as copper arsenic sulphides (enargite) and silver arsenic sulphides (tetrahedrite/polybasite) and some native gold (within pyrite).

The Mt Carlton deposit comprises two discrete zones: the large gold dominant V2 deposit and the smaller, silver rich A39 deposit. The V2 deposit is flat lying and situated 20 m to 180 m below surface and is 70 m thick with a 500 m by 500 m areal extent. The two deposits are located 200 m apart. Initially both deposits were mined and processed in 3 monthly campaigns, mining and processing of the A39 deposit was completed in August 2014, production now coming solely from the V2 deposit.

The main rock types are from an intrusive and extrusive felsic volcanic metamorphic ore complex. Sulphide veins dipping at moderate to steep angles to the NW host a majority of the known economic mineralisation. The ore lithology is predominately Rhyodacite with varying degrees of brecciation and silicification.

HISTORIC TESTWORK SUMMARY

Twenty samples with geographical details were subjected to comminution variability testing during the study phases of the project (Table 1). The test work undertaken included:

- Bond Ball and Rod Mill Work Indices
- Abrasion Indices
- SAG Mill breakage testing (SMC).

The 15th or 85th percentile rankings of the ore properties were used for design of the comminution circuits in the absence of a detailed lithology-based mining schedule.

The BWi variability was high with a coefficient of variance of 26.6 per cent. This variability made the design of a suitable circuit more complex particularly as the ore competency (Axb) variability did not correlate with the variability in BWi, which occurs for some ores.

Hole ID	Deposit	RWi kWh/t	BWi kWh/t	Ai	A	B	A*b	SG	ta
171	V2	20.7	19.4	0.61	100	0.24	24.0	2.75	0.23
244	V2	21.7	19.6	0.52	74.2	0.37	27.5	2.65	0.27
260	V2	20.1	17.5	0.42	90.6	0.30	27.2	2.73	0.26
480	V2	21.2	15.1	0.61	100	0.23	23.0	2.74	0.22
245	V2		20.4	0.67	100	0.25	25.0	2.76	0.23
164	V2		16.5	0.30	64.2	0.65	41.7	2.60	0.42
016	V2	28.8	22.6	0.80	88.5	0.37	32.8	2.61	0.32
254	V2		17.0	0.66	77.8	0.36	28.0	2.91	0.25
281	V2		21.2	0.45	100	0.25	25.0	2.78	0.24
300	V2	20.8	14.8	0.61	100	0.29	29.0	2.79	0.27
236	V2		20.7	0.11	68.3	0.43	29.4	2.64	0.29
238	V2	22.3	21.0	0.14	44.7	0.61	27.3	2.51	0.28
429	V2		15.1	0.63	95.5	0.27	25.8	2.76	0.24
329	V2		19.0	0.40	69.5	0.39	27.1	2.69	0.26
259	V2		18.6	0.43	77.8	0.31	24.1	2.69	0.23
447	A39		15.8	0.55	81.6	0.34	27.7	2.63	0.27
394	A39		19.4	0.47	98.7	0.30	29.6	2.70	0.30
227	A39		18.6	0.50	85.8	0.40	34.3	2.70	0.40
229	A39		17.3	0.53	77.1	0.40	30.8	2.70	0.30
370	A39		19.7	0.61	74.2	0.40	29.7	2.70	0.30
Average		22.2	18.5	0.50	83.4	0.36	28.5	2.70	0.28
Std Dev		2.99	2.26	0.17	15.2	0.11	4.26	0.08	0.05
CoV, %		**13.5**	**26.6**	**34.0**	**18.2**	**30.5**	**15.0**	**3.0**	**17.9**
Max		28.8	22.6	0.80	100	0.65	41.7	2.91	0.42
Min		20.1	14.8	0.11	44.7	0.23	23.0	2.51	0.22
85th %tile		**22.9**	**20.7**	**0.64**				**2.76**	
15th %tile					**69.3**	**0.36**	**24.9**		**0.23**

Table 1 – Historical Comminution Testwork.

CIRCUIT SELECTION AND DESIGN

Through a number of design reviews the following findings are noted:

- Two-stage grinding such as SAB or SABC is not recommended by OMC for the processing of these ore types as a result of the very high variation in power requirement in both SAG and ball mills. Mill selection for this large operating power range would not be practical. In addition, the grinding circuit will not be stable with two-stage grinding for these ore types.
- A tertiary crushing and ball milling circuit was also considered for increased processing stability. However, due to the high abrasiveness of the material, extreme wear rates on the secondary and tertiary crusher liners were predicted. Of the tested samples from Mt Carlton, the average Ai is 0.5 and the 85th percentile is 0.64, which reflect the 84th and 94th percentile of the OMC testwork database (+3,000 samples) respectively. The stability achieved would therefore come at a high maintenance and capital cost (low availability or a requirement for standby units). For these reasons the tertiary crushing circuit configuration was not selected.
- Following investigations and discussions on the use of different comminution circuit configurations, the use of single stage SAG milling was determined to be the best option for the Mt Carlton project. This configuration is best suited for high variability ore characteristics. It also provides the simplest flowsheet with the smallest foot print and minimises material handling. This combined with the expectation that this circuit will have the lowest operating cost has led to the recommendation of a single stage SAG mill circuit with recycle crusher.

Given the importance of a constant feed and product size for their downstream flotation performance, a detailed economic comparison of the single stage SAG mill with recycle crusher and tertiary crush – ball milling option was carried out. The conclusion to this study was the selection of the single stage SAG mill with recycle crusher circuit configuration.

The target throughput for this project in the final study was set at 800,000 tpa (or 100 tph) and a product P_{80} of 106 µm was nominated for the grinding circuit.

DESIGN CRITERIA

Table 2 summarises the selected design criteria for comminution circuit modelling.

The selected 7.32 m diameter SAG mill detailed in Table 3 was an available cancelled order mill which was deemed to be acceptable for the duty in the design modelling phase.

Item	Unit	Value	Reference
Ore Throughput	Dry t/a	800,000	Client
Operating Hours	h/a	8,000	Assumed
Feed Rate	t/h	100	Calculated
Product P_{80}	µm	106	Client
Ore Characteristics			
Ai - **Design** (Range)		**0.637** (0.114 – 0.800)	Testwork
RWi - **Design** (Range)	kWh/t	**22.9** (20.1 – 28.8)	Testwork
BWi - **Design** (Range)	kWh/t	**20.7** (14.8 – 22.6)	Testwork
A - **Design** (Range)		**69.3** (44.7 – 100)	Testwork
b - **Design** (Range)		**0.36** (0.23 – 0.65)	Testwork
A x b - **Design** (Range)		**24.9** (23.0 – 41.7)	Testwork
ta - **Design** (Range)		**0.23** (0.22 – 0.42)	Testwork
SG - **Design** (Range)		**2.76** (2.51 – 2.91)	Testwork

Table 2 – Design Criteria.

Equipment specifications

The primary jaw crusher is Terex JW430 (Dimensions 1070 x 760) with a 110 kW motor. The crusher is operated at a 100 mm closed side setting. The specifications for the 3.6 MW SAG mill are shown in Table 3. The SAG mill is fitted with a trommel, 2.347 m diameter by 2.765 m long fitted with 12 x 20 mm and some 15 x 20 mm apertures screen panels. The pebble crushers are Sandvik CH420 cone crushers with 90 kW motors designed to operate at a closed side set of 10 mm. The cyclones are a cluster of 8 Weir CVX400-111 with 140 mm vortex finders and 90 mm spigots.

Parameter	Unit	SAG Mill
Mill Diameter (Inside Shell)	**m**	**7.32**
EGL	**m**	**3.80**
Imperial Measurements	ft x ft	24.0 x 12.5
Liners Thickness and Type	mm	100 (Steel)
Speed Mill	% Nc	Variable 55 – 67- 80
Speed Motor	rpm	820 - 985- 1182
Maximum Ball Charge	%	15
Mill Total Load - Duty	%	25
- Maximum	%	35
Duty Power Requirement		
Mill Speed	% Nc	75
Ball Charge	% Vol	8
Pinion Power – Duty	kW	2,490
Installed Power (@ 80% Nc)	**kW**	**3,600**

Table 3 – SAG Mill Specification.

Single stage SAG mill modelling

The mill simulations to confirm the selection of 7.32 m diameter mill were based on the OMC power model. The model combines proprietary and published power models to predict the total specific energy and the specific energy for each of the components of the comminution circuit (Scinto, Festa and Putland, 2015). The expected design power utilisation and range for the Mt Carlton Project is shown in Table 4.

The average SAG milling specific energy was determined to be 24.1 kWh/t and the 85th percentile (design) 24.9 kWh/t. The variation in the SAG mill power requirement for this configuration was predicted to be approximately 700 kW which would be controlled with mill speed, total mill load and adjustment of the proportion of pebbles crushed.

The 7.32 m diameter mill was predicted to draw up to 3320 kW at the pinion with a 15% ball charge, 75 per cent Nc and 35% total load. The 85th percentile ore requirement of 24.9 kWh/t was predicted to be achieved with an 8 per cent ball charge, 75 per cent Nc, 25 per cent duty load.

The requirement for a pebble crusher was borderline and was included in the design to reduce risk. Consideration of up to 75 t/h pebble extraction was noted for design if the circuit was ever to be expanded to two stages.

The 75 t/h crushing rate is higher than is required for single stage utilisation. The installation of one crusher for half the capacity was used as the basis of design of the single stage circuit with the ability to add a second crusher as standby or for expansion if required. A 90 kW cone crusher was selected for the duty.

Parameter		Unit	SS SAG Mill
Feed Rate		Tph	100
Feed Size, F_{80}		Mm	125
Product Size, P_{80}		µm	106
Pebble Recycle	- Average	% Feed	25.0
	- Range	% Feed	25.0 – 37.5
Power Utilisation			
SAG Milling Specific Energy	- Design	kWh/t	24.9
	- Range	kWh/t	20.0 - 27.0
Specific Recycle Crushing Energy		kWh/t	0.5 – 0.75
Total Circuit Specific Energy	- Design	kWh/t	25.5
	- Range	kWh/t	20.6 - 27.6
$F_{(SAG)}$	- Average		1.35
	- Range		1.19 - 1.53
SAG Mill Pinion Power	**- Average**	**kW**	**2490**
	- Range	**kW**	**2000 - 2703**

Table 4 – Power Utilisation – Single Stage SAG Mill.

Process description

Ore at Mt Carlton from open pit mining is truck dumped or fed by front-end loader (FEL) into the run-of-mine (ROM) bin. The ROM bin has a static grizzly to protect the jaw crusher from oversize lumps. Ore is withdrawn from the ROM bin by a vibrating grizzly feeder. The grizzly oversize cascades into the jaw crusher before being discharged and conveyed to the coarse ore stockpile. The grizzly undersize discharges onto the same conveyor as the jaw discharge for transport to the stockpile.

Primary crushed ore is reclaimed from the stockpile by two apron feeders onto the SAG mill feed belt to feed the SAG mill. SAG mill feed is combined with recycle crusher product, cyclone underflow and inlet dilution water to achieve the correct milling density. The SAG mill discharges over a trommel with the undersize material reporting to the cyclone feed hopper. The trommel oversize passes through magnets to remove tramp metal while being conveyed to a pebble crusher feed bin. Pebbles are withdrawn by one of two feeders into one of the pebble crushers or overflow the bin and bypass the crushers. The crushed and uncrushed pebbles are conveyed back onto the mill feed conveyor.

The mill trommel undersize is diluted with water to achieve the correct density prior to pumping to the cyclones. The cyclones classify the ground slurry with the cyclone overflow at the target grind size reporting as product to the trash screen. The coarse underflow gravitates back to the SAG mill for further size reduction.

COMMISSIONING AND RAMP-UP

Commissioning was originally anticipated to be complete in early 2012, however due to delays during the engineering and construction phases, commissioning was delayed until December 2012. The mill discharge configuration was modified in December 2012 by replacing two of the twenty-four grate segments with pebble ports as it was believed the mill would not be able to achieve design throughput without achieving the design pebble crushing rate. The commissioning ore selected was low grade ore from the silver rich A39 deposit to optimise available ROM stocks, considering the mining schedule and need to meet concentrate supply requirements

The crushing circuit was effectively commissioned in January 2013 with approximately 3,500t of commissioning ore crushed, then suspended until March 2013 whilst the remainder of the plant was completed. Ore commissioning of the remainder of the plant commenced on 20th March 2013. The grinding, flotation and filtration circuits were all commissioned by the end of March 2013, with saleable concentrate being produced within the month. The regrind circuit was commissioned in July 2013, however not operated until September 2013.

Ramp up to design targets was scheduled to take four weeks following commissioning, with budget feed to commence in Week 3 and a throughput of 100t/h forecast by Week 4. The plant was scheduled to treat two discrete orebodies in three monthly campaigns, there were ramp up allowances factored into the first campaign of V2 ore scheduled for July 2013. Plant utilisation was the largest single factor preventing the plan being achieved, as shown in Figure 2. The grinding circuit performed well during the ramp up phases, although design mill throughput was not able to be achieved on a consistent basis due to downstream process issues of which the concentrate bagging system had the largest impact on both utilisation and mill throughput rate. Modifications to the concentrate bagging system in June 2013 realised a significant improvement in mill utilisation, however the milling rate was still detrimentally impacted by the bagging system capacity with further improvements made in 2014. Consistent mill throughput rates of 100t/h were achieved for short periods in September 2013; however it was not until June 2014 that the design throughput rate of 100t/h was sustainably achieved. The grind was however coarser than design.

The first concentrate shipment of A39 concentrate was dispatched on the 15th of May 2013, with the first campaign of A39 ore ceasing on 30th June 2013. The first campaign of V2 ore commenced 2nd July 2013 and whilst similar issues with the bagging system capacity were experienced; the ore performed better than expected. Saleable concentrate was produced from the start of the campaign with the first shipment of V2 concentrate dispatched in August 2013.

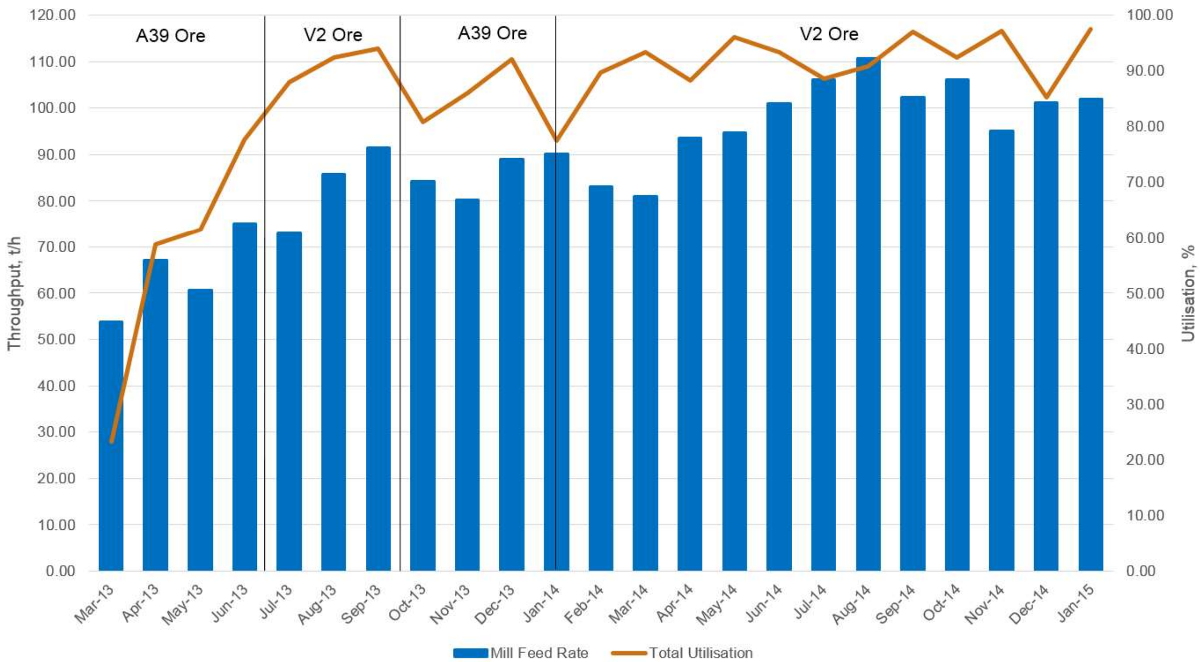

Figure 2 – First 12 months of operations.

OPTIMISATION

A site visit and circuit performance review was undertaken by OMC in November 2015. This involved a review of production data, operating philosophy and a grinding circuit survey conducted on the 21st of November, 2015.

The production data suggested that the design throughput (100 t/h) was being achieved at an average COF P_{80} of 120 µm. The ore treated during the survey was found to be softer than the design, although within the historical testwork range for the fresh ore. The survey data was used to fit a JKSimMet model in order to verify recommendations made during the site visit.

The following were the key points and recommendations of the optimisation study:

- OMC uses an 'f_{SAG}' efficiency factor (Siddall, Henderson & Putland, 1996) for determining total grinding circuit specific energy. The power required for the grinding circuit standardised to an F_{80} of 150 mm and P_{80} of 75 µm is compared to the Bond BWi based power that is theoretically needed to effect comminution from the same size range. The ratio of the two values is referred to as the 'f_{SAG}' efficiency or design factor. To determine the efficiency of an operating grinding circuit, OMC compares the actual f_{SAG} of the plant to the theoretical value calculated using testwork results. The power consumption of the SAG mill compared to the theoretical power consumption based on the test work shows that the circuit was operating inefficiently, with f_{SAG} values over 1.4, compared to the predicted

f_{SAG} of 1.25 for the ore surveyed (see Table 5). This indicates that the circuit was using approximately 22 per cent more energy than it should be for the duty, or possibly the tested ore characteristics were not representative of the processed ore. A high fines content was observed in the cyclone overflow, indicating that sliming may be contributing to the observed inefficiency.

- SAG mill speed was not used as much as it should be due to the operating conditions in the SAG mill, where the pebble ports were resulting in too much of the rock media being extracted and crushed. Without the ability to sustain a sufficient rock load, it was not possible to increase the speed as this would result in the charge striking the shell plates of the mill. A suggested grind and load based control philosophy was provided for use in conjunction with the recommended set point changes. It is worth noting that the survey ore characteristics were notably softer than the design characteristics, particularly survey the Axb value of 37 compared to the design value of 24.9. As such, a high pebble extraction rate is not needed to maintain throughput for the current ore type, however this may need to be re-assessed if the feed blend becomes more competent in the future.
- At the time of the OMC site visit, the SAG mill was operating at a low speed of 67 per cent Nc, couple with a relatively high ball charge of 12.5 per cent to compensate for the reduced power draw at the low speed. The total load was low at 18-25 per cent. These conditions result in operation at close to the maximum rotor current (maximum power draw for the operating speed). The drawn power at 2.6 MW was just enough to achieve the target throughput and grind, however, it limited the operating range for the mill and contributed to much higher than design media consumption rates (actual 3 kg/t vs predicted 1.9 kg/t). Following the assessment of the survey data, it was also suspected that operating at such a low speed is contributing to the observed energy inefficiency. It was recommended to move away from the current mode of operation by reducing the ball charge and increasing the operating mill speed. This required a reduction in the current kinetics of coarse rock breakage in the SAG mill to ensure that a sufficient rock load can be maintained in the mill at the higher speed.
- To reduce the coarse rock breakage kinetics, it was recommended that the two pebble port sections be removed to limit the amount of fine media being removed. This would reduce the average diameter of the balls in the mill. If this was not sufficient, the amount of 105 mm media was to be increased gradually in the top-up blend (base case blend was 50 per cent 105 mm, 50 per cent 125 mm).
- Simulations indicated that under the above conditions, the ball charge may be reduced to 9 per cent, and by increasing the speed to 75 per cent, the current throughput and grind could be maintained with an adequate load level in the mill. This is a significant reconfiguration of the circuit and required a gradual transition with the mill speed increased only as the charge facilitated to prevent destruction of the load and liner damage.
- It was not recommended that recycle crushing was utilised, as the throughput was higher than design and the target grind coarser. Recycle crushing is typically used in SS SAG circuits to assist in coarsening the grind where coarser grinds are targeted, however if the rock is competent it is more inclined to hold up in the mill and over-grind. Recycle crushing could be required in the future when harder ore closer to the design range is treated, however was not currently required.
- Reducing the ball charge to 9 per cent and removing the ported sections of the mill was predicted to reduce the media consumption rate by 36 per cent, a significant operating cost saving. While it was also envisaged that energy efficiency would improve, it was not possible to estimate this effect with the current model. It was recommended that a second survey be conducted following the implementation of the above changes to provide a new benchmark for further optimisation.
- The data collected during the survey showed that the shape of the overflow PSD is somewhat unconventional, as there appeared to be excessive fines generation in the circuit with a poor water split to overflow. The cyclones were achieving a relatively efficient cut based on a reduced efficiency curve when the effect of the water split was removed. A fitted alpha value of 2.94 was produced using the survey data, although a fishhook was observed in the partition curve (Figure 3).
- Increasing the recirculating load could assist in reducing sanding in the discharge hopper. The circulating load was 130 per cent at the time of the survey. By reducing the vortex finder to 110 mm and maintaining a spigot size of 90mm, the recirculating load could be increased to 200 per cent with 3 cyclones operating. The Vortex to spigot ratio was low in this case which is not typically ideal for optimal performance. Alternatively, if the overflow density can be reduced to 40 per cent solids w/w, the same effect can be achieved without changing the vortex finder, which would allow for better classification efficiency. The current overflow density was much higher than design at 48-50 per cent solids. Increasing the recirculating load should also assist in reducing the sliming that was observed in the circuit, improving the milling efficiency. A combination of the two approaches, three cyclones with a smaller reduction in vortex finder size and reduced overflow density would provide the best outcome.

- A constant feed flow (constant pressure) control philosophy was recommend for be implementation to improved circuit stability.

Parameters	Units	Design	Model Survey	Actual Survey	Production Data
Ball Mill Work Index	kWh/t	21.0	17.6	17.6	17.6
Axb	kWh/t	24.9	37.0	37.0	37.0
SAG Mill					
Net SAG Milling Rate	t/h	100	108	108	97.6
SAG Mill Pinion Power	kW	2491	2041	2493	2347
SAG F_{80}	µm	125000	100000	100000	100000
SAG Mill P_{80}	µm	106	148	148	118
POWER UTILISATION					
SAG Milling Specific Energy	kWh/t	24.9	18.9	23.1	24.1
Specific Recycle Crushing Energy	kWh/t	0.55	0.00	0.00	0.00
Total Circuit Specific Energy	kWh/t	25.5	19.0	23.2	24.1
f_{SAG}		1.21	1.25	1.46	1.42

Table 5 – Mt Carton Milling Circuit Power Utilisation.

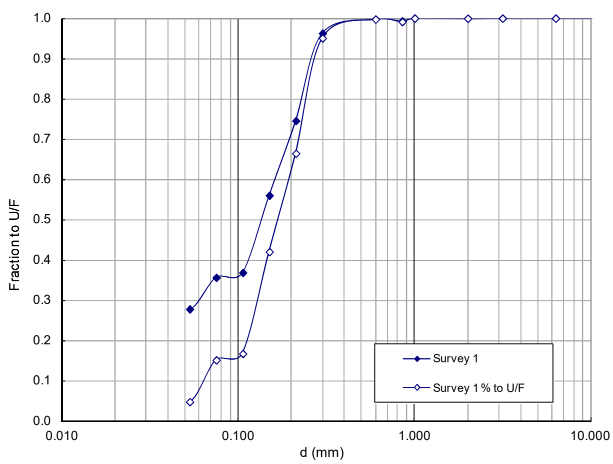

Figure 3 – Mt Carlton Partition Curve.

During 2016 site personnel did excellent work implementing most of the optimisation strategies developed with OMC, which had a significant impact on plant performance.

Pebble ports where removed from the grates, reducing the average ball size diameter and consumption in the mill. The smaller ball diameter reduced impact breakage, allowing the mill to operate at higher speed and under more autogenous conditions. This increased efficiency and utilised more installed SAG mill power. The cyclone operation was changed to constant pressure and the vortex finder size was decreased improving cyclone performance. The removal of the pebble ports has facilitated a change in the mill operating speed from an average of 62.5 per cent Nc to 70.4 per cent Nc after the change. This allows higher SAG mill power utilisation. Before the change, the SAG mill power utilisation was about 65.1 per cent. This increased to 72.4 per cent post the grate change. An analysis of production data following the change in 2016 showed 80 per cent SAG mill power utilisation.

Looking at the production data, it can be seen that the product size was more variable before the pebble ports were removed. The grind size then became even more consistent following the change to 110 mm vortex finders. After the removal of the pebble ports the circuit product size becomes finer as the liner set wears. This is a result of decreased impact breakage as the effectiveness of the lifters diminishes. The grinding action becomes more abrasive over the life of the lifters. The operating work index also appears to increase dramatically towards the very end of the- lifter life. Comparing the pre and post pebble port removal production datasets, the impact of the changes becomes apparent (see Table 6).

Parameter	Units	Pre	Post	Change	% Change
Mill Feed Rate	t/h	95.0	97.3	2.3	2.4%
SAG Mill Speed (% of critical speed)	%Nc	62.5	70.4	7.9	12.7%
SAG Mill Power	kW	2345	2609	264	11.3%
Daily Grind Size (P_{80})	µm	115	89	-27	-23.3%
SAG Mill Specific Energy	kWh/t	23.1	24.7	1.6	6.8%
Operating Work Index – Wio	kWh/t	25.4	23.7	-1.7	-6.5%
f_{SAG}		1.35	1.32	-0.03	-2.5%

Table 6 – Pre (Nov 2015 – Feb 2016) and Post (Mar 2016 – Jul 2016) Pebble Port Removal.

Removing the pebble ports has reduced the average ball size in the mill, preserving rock media, which has allowed the mill to run 12.7 per cent faster with an 11.3 per cent increase in power draw when combined with a slight reduction in ball charge. This additional power has been used to grind 2.4 per cent more throughput while achieving a 27 µm reduction in product size. This reduction in grind size has been achieved with only a 6.8 per cent increase in specific energy consumption because of the 6.5 per cent average increase in grinding efficiency as expressed by the operating work index. The energy efficiency is now only slightly higher than would be expected based on the last plant survey ore characteristics. An improvement in the water split to overflow in the cyclones would be expected to reduce fines generation further, bringing the grinding efficiency in line with theoretical.

Before the pebble port change, the grinding media consumption was 3.02 kg/t, over twice that of the design. After the change the ball consumption has been 2.16 kg/t. This represents savings close to a million dollars per annum. In the later months of 2016 ball consumption levelled out at around 2.4 to 2.5 kg/t. This higher value is a result of the higher average power draw being sustained (2890 kW compared to 2345 kW) and subsequently the finer grind size. Ball consumption is technically defined and calculated as kg/kWh, where kg per tonnes depends on how fine the grind is and the consumed specific energy. This ball consumption rate is still a considerable savings at around 20 per cent. If the equivalent power draw could have been drawn under the pre-operating conditions (which it can't because of rotor current restrictions), the ball consumption would be expected to be well over 3.5 kg/t based on the historical consumptions rates. The blend of 50 per cent 125 mm and 50 per cent 105 mm steel balls currently being used appears adequate for the current duty. If a higher throughput and a coarser grind were to be targeted, a higher portion of 125 mm balls could be used as the SAG mill is now close to being lump rock limited.

The SAG mill is currently not the circuit bottleneck, achieving the design capacity at a finer than design grind size. Ball consumption and energy efficiency have been optimised at the current plant capacity.

Further optimisation is still ongoing with a number of new initiatives identified in the review following the original optimisation study. These initiatives may include:

- Implementation of expert control for the grinding circuit (feed rate and SAG mill speed), including a historian for the SCADA system.
- Review and optimisation of the SAG mill liner design.
- Consideration of a change to water addition to control the discharge hopper level and a move to operation at a lower cyclone overflow density. Water addition is currently adjusted to achieve the target cyclone overflow density. This change will improve the water split to underflow and reduce over-grinding (fines content in the overflow PSD). This could be trialled and the grinding circuit re-surveyed. This will provide an updated baseline for a second round of optimisation. Given the importance of the selected overflow density to both grinding and flotation, two surveys maybe undertaken; one at the current overflow density (+42 per cent solids) and one at the overflow density optimal for comminution, circa 35 per cent solids. The high cyclone overflow density is being driven by flotation requirements. As such sampling of the flotation circuit at the same time is being considered. This would form the basis for a holistic optimisation of not just grinding but also metal recovery.
- Site personnel are considering tracking ball consumption per kWh basis to assist with determination of media addition.

- Consideration of undertaking a throughput / grind / recovery study for the project.

CONCLUSIONS

A primary crush-SS SAG circuit with pebble crushing was selected for the Mt Carlton project. The need for pebble crushing was subject to ore competency, where it was envisaged that the competent design ore with an Axb of 24 would require pebble crushing to ensure the design throughput could be achieved. Following the commissioning and during subsequent optimisation exercises, it was identified that the mill was performing inefficiently and consuming excessive media. Furthermore, the power utilisation of the available SAG mill power was poor, at 65 per cent. The optimisation studies identified that the ore being treated was softer than design, and as such the configuration of the mill was not suitable for the actual ore type being treated. A more appropriate configuration was recommended including mill load, speed, control philosophy, grate configuration and cyclone operation which is summarised below. Another review of the operating conditions will be required if the ore competency of the mill feed changes in the future. Key conclusions are as follows:

- The Mt Carlton deposit comprises two discrete zones: the large gold dominant V2 deposit and the smaller, silver rich A39 deposit. The comminution testwork indicates the ore is competent and variable. This variability made the design of a suitable circuit more complex, particularly as the ore competency (Axb) variability did not correlate with the variability in BWi.
- A number of option studies and design reviews identified a single stage SAG circuit with recycle crusher as the most suitable option for Mt Carlton to suit the variable ore characteristics. It was also the simplest flowsheet examined and was predicted to have the lowest operating cost. Detailed modelling showed that the requirement of a pebble crusher was marginal; however this was included to reduce design risk by giving more control over the grind.
- A Ø7.32m x 3.80 m EGL, 3.6 MW SAG mill was selected for the SS SAG duty. A Terex JW430 was selected for the primary crusher duty and Sandvik CH420 for the recycle crusher.
- The plant was commissioned by March 2013 with saleable concentrate produced within the month. Design throughput was not achieved until June 2014 due to a series of issues including below-design plant utilisation and downstream constrains such as the concentrate bagging system, which required de-bottlenecking.
- A grinding circuit review conducted by OMC in November 2015 found that the circuit was operating inefficiently, with f_{SAG} values over 1.4, compared to the predicted f_{SAG} of 1.25 for the ore surveyed. The SAG mill speed was not being used to its full ability, and operating with a high ball charge with low total load meant the mill was operated at close to the maximum rotor current. Grinding media consumption rates were also excessive with the high operating ball charge, at 3kg/t.
- A series of simulations were conducted which lead to recommendations that were implement by the Mt Carlton operation team. The key modifications made were as follows:
  - Pebble ported segments were removed from the SAG mill discharge and replaced with fine grates to reduce the average ball size diameter and media consumption rate. This increased efficiency and allowed for utilisation of more of the installed power.
  - The cyclone control philosophy was changed to constant pressure (flow). The vortex finer size was decreased to increase the recirculating load. This improved circuit stability, which was subject to surging prior to the changes and sanding in the cyclone feed sump.
  - Removal of the pebble ports allowed for the SAG mill load to be increased to a point where the mill speed could be increased. This in turn led to the overall SAG mill power utilisation increasing from 65.1 per cent to 80 per cent. The additional power has been used to achieve a finer product size P_{80}, down from 115µm to 89µm. An increase of 2.4 per cent in through has also been observed.
  - Both an improvement in grinding efficiency and media consumption were also observed, with the latter down by 20 per cent.
- Following the optimisation in 2015, the milling circuit is no longer the plant bottleneck, achieving design throughput at finer than design grind size. Further optimisation is planned in the following areas by the site team:
  - Implementation of expert control for the grinding circuit (feed rate and SAG mill speed), including a historian for the SCADA system.
  - Consideration of a change to water addition to control the discharge hopper level and a move to operation at a lower cyclone overflow density.

- Review and optimisation of the SAG mill liner design.
- Consideration of undertaking a throughput / grind / recovery study for the project.

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