SAG 2006

DEPARTMENT OF MINING ENGINEERING
UNIVERSITY OF BRITISH COLUMBIA
Vancouver, B. C., Canada

DEVELOPMENT OF A SAG MILL SHELL LINER DESIGN AT CADIA USING DEM MODELLING

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ABSTRACT

In August 2001, Newcrest Mining contracted Conveyor Dynamics, Inc. to develop a model that would predict wear life of the Cadia 40 ft. SAG mill shell liners, and then provide an alternative design to improve liner life and mill capacity. Following a 7 month Discrete Element Method (DEM) study, a liner profile was finalised. This was further refined by the casting supplier, Bradken, and a set of 12 rows of trial liners were fabricated and installed.

Following successful trials a full set of liners was installed in April 2003. Key features of the new design were a 52-row "Hi-Lo" lifter at 422mm and 300mm height above the plate, 28-degree face angle and mini-lifters that reduced scalloping between the main lifters. Five sets of the new liners have been installed and predictions of wear life have proven themselves. This paper presents the results to date and future plans in developing lifters for the world's largest diameter SAG mill.

INTRODUCTION

Newcrest Mining Ltd owns and operates the Cadia Valley Operation (CVO) located 25km from the city of Orange in New South Wales. The operation consists of a large tonnage and low grade open cut mine and concentrator (Cadia Hill) as well as a smaller tonnage higher grade underground mine and separate concentrator (Ridgeway). Combined

throughput is around 22Mtpa; producing on average 600,000 ounces of gold and 200,000 tonnes of copper concentrate per annum. The Cadia Hill grinding circuit liner design has been the subject of much design effort over the past 8 years (Hart et al, 2001). The Cadia SAG mill, commissioned in 1998 is 40 feet in diameter and 22 feet long with an installed capacity of 20MW. It is supported by 2 ball mills each 22 feet in diameter and with a combined capacity of 19.4MW.

At the time of the last SAG conference in 2001, Newcrest were embarking on the next phase of liner design for Cadia that would improve the liner life by an additional month, without compromising production targets. In order to make these changes, Newcrest had engaged the service of Conveyor Dynamics Inc (CDI) to assist with modeling and optimization of the Cadia SAG mill shell.

SAG SHELL LINER DEVELOPMENT AT CADIA

A chronology of shell liner history from June 1998 to February 2006 is summarised in Table 1. The face angle reported here refers to the predominant angle on the lead side of a lifter. Lifter height refers to the height protruding above the plate, and plate thickness on the lead side of the lifter has been used for this summary (In some designs the plate thickness is different on the lead and lag side of the lifter).

Four key milestones in this brief history have been;

- A change from 78 rows of Hi:Lo, 12 degree face angle lifters to 52 row of Hi:Hi, 25 degree face angle lifters in Dec '98
- Increases in the face angle from 25 to 30 degrees and composite 30/40 degrees between Dec '98 and Feb '01.
- Move to single direction mill rotation in Jul '01
- Installation of the CDI liner design in December '02

These periods are further detailed in Table 1 (next page) which summarises all 19 liner sets used in the Cadia SAG mill project to date. The following points should be noted from Table 1:

- Set 1 – The commissioning set was not used in the data analysis.
- Set 16 – This comprised a 50% CDI design and 50% old design (stock which had to be consumed). The liners were pulled out early and results excluded from data analysis.

Table 1: Chronology of Cadia SAG Mill Shell Liners 1998 - 2006

Set No.	Date Installed	Face Angle (deg)	Lifter Height (mm)	Plate Thickness (mm)	Total Mass (t)	Liner Type and Conditions
1	Jun 98	12	254	89	297	78 Row Bi-Direction
2	Dec98	25	255	90	293	52 Row Operating Bi-direction Rotation
3	Jun 99	25	245	100	309	
4	Nov 99	30	245	100	309	
5	May 00	30	245	100	309	
6	Oct 00	30	245-265	100	323	
7	Feb 01	30/40	250	115	351	
8	Jul 01	30/40	250	115	351	52 Row Design Modified For Single Direction
9	Nov 01	30/40	260	135	372	
10	Mar 02	25	290-330	115	373	
11	Aug 02	25	330	115	380	
12	Dec-02	25	330	115	380	
13	Apr-03	28	422/300	145	420	52 Row CDI Design Operated in Single Direction
14	Sep-03	28	422/300	145	425	
15	Feb04	28	422/300	145	427	
16	Jul-04	28/25	422/330	145/115	405	
17	Nov-04	28	422/300	145	427	
18	Apr-05	28	422/300	145	427	
19	Sep-05	28	422/300	145	427	

Although the 52-row design had improved operating conditions over the 78-row design, there still remained a number of limitations of this design that had to be addressed. These were related to;

- Occasional packing of the lifters occurred immediately following a mill reline. Although not as severe as observed with the 78 row Hi:Lo design it was still present for a week or two after start up.
- High noise levels and occasional ball breakage following a shell reline which necessitated operating the mill at low speed following start up. Over the life of the liner the speed wasincreased from 8.6rpm (71% critical speed) to 9.6rpm (79% critical speed). A quicker ramp up of the mill was sought.
- High noise levels arose once the mill direction was reversed (usually a month to six weeks after the reline). Hence there was a further requirement to operate the mill at slower than optimum speed for a second time.
- In an attempt to reduce the effect of ball overthrow the lifter face angle was increased to 30 degrees and eventually a composite

- 30 and 40 degree face angle lifter was installed. However, the higher face angle and composite face angle lifters generally gave a lower life.

These issues were investigated in consultation with Bradken and resulted in minor changes to the design and a move to a single direction mill rotation.

The change from bi-directional mill rotation to single direction mill rotation in July 2001 was precipitated by extremely high wear in the pulp lifters of the 40-foot mill following commissioning (Hart et al 2001). The original sets of rubber outer pulp lifters were worn out after 6 months operation and chrome moly steel had only increased life to around 11 months. The outcome of the move to a curved discharge end design was improved pebble removal (throughput rates increased) as well as an increase in life of the pulp lifter components (outer and middle pulp lifters) to over 3 years.

The change to single direction rotation was expected to impact the life of the SAG mill shell, and in order to minimise the effect of this CVO and Bradken commenced design changes for a new liner design, in June 2001. These changes were initially limited by the extent of modifications that could be made to the existing patterns, hence some of the early designs were less than optimal. Detailed monitoring of the shell liner wear profiles was undertaken in 2000 and 2001 in order to provide input in to this process and aid future design improvements.

Examples of the liner profiles taken for both Bi-directional and single direction mill rotation are presented in Figures 1 and 2(next page). The “Pin Number” in these charts refers to measurement gauge points at 40mm centers and 50mm in from the ends.

As a result of the switch to single direction mill rotation the average shell liner life reduced from 144 to 118 days (an 18% reduction). Had this not been addressed, it would have necessitated an additional mill reline every 2 years (at an expected cost of around $1.2million). This would have severely impacted on the benefits gained from operating with the curved discharge end.

The 2 liner sets installed immediately prior to and after the change to single direction rotation were identical in profile, mass and casting supplier and were monitored closely in the period leading up to and following the decision to change from single to bi-directional mill rotation.

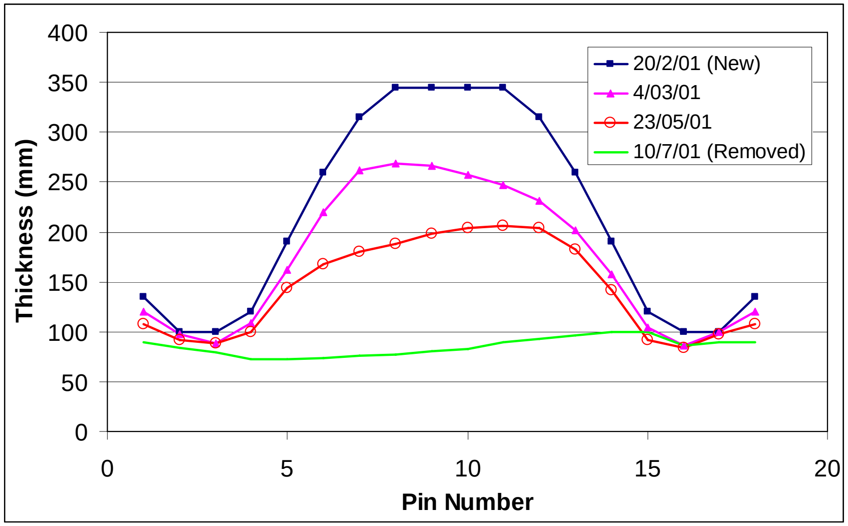

Figure 1: Shell Liner Profile with Bi-Direction Rotation Feb 01

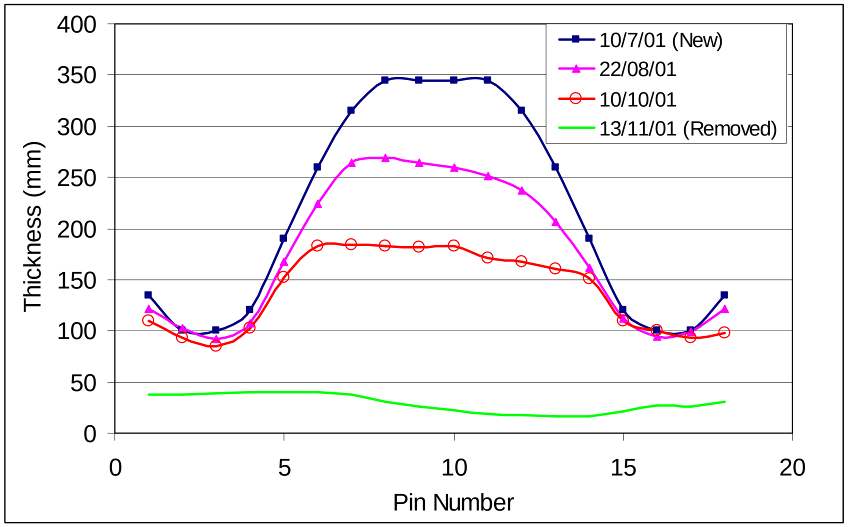

Figure 2: Shell Liner Profile with Single Direction Rotation Jul 01

The reduction in life of the single direction liner set was around 10% based on the number of days life and tonnage ground. Given the much lower liner profile at removal, Figure 2 compared to Figure 1, the true

extent of the change to single direction rotation was probably closer to a 15% reduction in life.

As a result of these observations, lifter heights were increased by 80mm and lifter face angles revised during successive installations in an attempt to return liner life to the previous levels.

DEVELOPMENT OF A WEAR MODEL AND NEW LINER DESIGN FOR SINGLE DIRECTION MILL ROTATION

In parallel with the site based efforts from CVO and Bradken, CDI were engaged to develop an alternative profile suited specifically to the single direction mill rotation. CDI had been modeling SAG mill performance through DEM simulations for a number of years and had previously presented their work (Herbst and Nordell, 2001, Nordell et al, 2001). The project scope for CVO was to conduct SAG mill performance monitoring and modeling, as well as assess wear behavior with Discrete Element Method (DEM) simulations. Wear profiles and operating data, from known production periods, were provided as well as constraints that CDI would have to work within (such as the liner handler lifting capacity, wear materials, bolting arrangement of the shell and the extent of risk that CVO were prepared to accept).

CDI were to use data from the 2 production periods (leading up to and following the change to single direction mill rotation) to “tune” their wear model and predict the wear life and profile of a third set of liners (set 9), which was installed in November 2001. They were then to provide a liner profile which would be developed to a “trial” casting stage and if acceptable to CVO would then be used for full plant production.

Through analysis of a series of alternative wear profiles DEM modeling was expected to demonstrate improvements in the following key areas;

- Increased comminution rate (tph) or finer grind size P_{80}
- Reduced specific power consumption (kWh/t)
- Greater lifter/liner wear life (tonnes milled/grinding hour)
- Reduced liner mass installed per tonne of ore ground (kg/t)
- Increased mill speed ramp up following liner replacement
- Optimisation of liner bolt pattern and torque.

In order to achieve higher throughput rates it was recognized that the ore charge circulation rate per revolution would need to be increased, a higher specific pressure in the comminution zone maintained and the area of comminution inside the mill increased also.

To increase liner wear life it was necessary to increase liner mass in order to overcome the ores abrasion properties. The ore charge motion was designed to minimise cateracting and the allowable ball impact impulse to a level below its critical fatigue fracture limit. This would ultimately allow the movement towards harder metals with better abrasive resistant properties. Increasing the mass of lifter inside the mill without consideration of the above DEM modeling has often led to worse comminution performance. However, the profile and size of the lifter design was expected to produce a favorable result in this case.

The initial studies were tailored to minimise any expectation of risk by maintaining a 52-row liner configuration. A high-low liner pattern was proposed to enable the higher 26 lifter set to be 28% higher than the existing design developed by CVO and Bradken. This configuration was predicted by DEM analysis to increase life by 20% and comminution by about 6%.

Figure 3 illustrates DEM predicted throughput for several of the lifter configurations studied during the design stage;

- 2x30&40 - Bi-direction design and rotation (Set 7)
- 2x30&40_Uni. Bi-direction design run single direction (Set 8)
- 1x30&40 – Uni-direction design and rotation (Set 9)
- CDI 7 – CDI uni-direction design (Set 13 on)

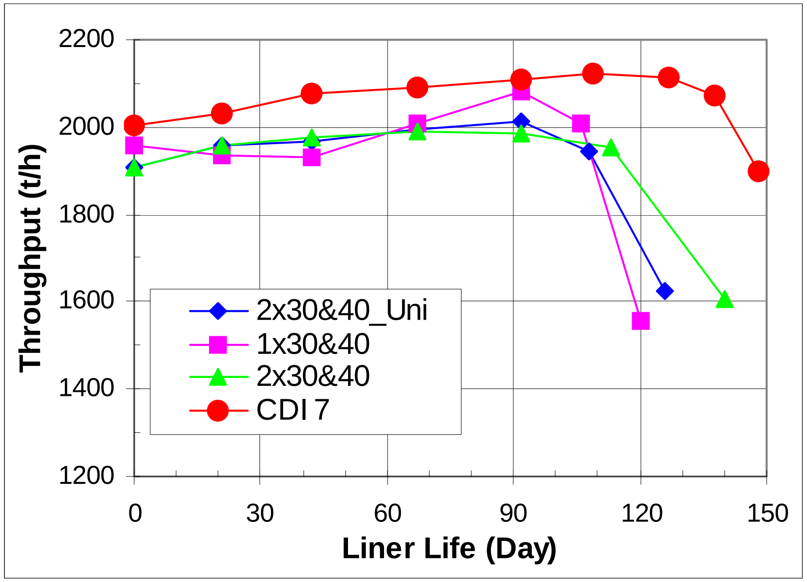

Figure 3: DEM Predicted Throughput versus Liner Life Performance

Mill performance data was provided for sets 7 and 8. The predictions for sets 9 (and ultimately set 13) compared favorably with the measured values. Liner Set 9 was a Uni-direction design and Uni-directional operation. It had a measured average tonnage rate of 2140 t/h over a liner life of about 116 days, which totaled 6.0 million tonnes for the Set. Table 2 summarises the results;

Table 2: Comparison of CDI Model and Actual Performance – Set 9

Set 9 Performance	Life (days)	Tonnes (Mt)	Specific Power (kWh/t)
Prediction	120	5.65	8.74
Actual	116	6.00	8.50
Variance %	-3.3	+5.8	-2.4

Actual throughput rates were much better with this set than the model predicted (life was slightly lower). This was attributed to the fact that approximately 0.6Mt of tertiary crushed Ridgeway ore was fed to the SAG mill along with Cadia Hill ore during the life of this set (the model had been based on Cadia Hill SAG feed only). The Ridgeway ore was already finely crushed (P_{80} = 12mm) and quickly passed through the mill. Simulation studies carried out at the time indicated that 1tph of Ridgeway ore displaced 0.3tph of Cadia Hill ore. Adjusting the throughput rate for this gave an average of 2010tph and an equivalent total throughput of 5.60Mt, extremely close to the model prediction

This result provided sufficient confidence in the model such that the proposed liner profile CDI 7 was taken through to the design and implementation phase.

The final deliverable of this study was to predict the life, throughput rate, energy efficiency and wear profile of the new liner design, CDI 7.

A comparison of predicted versus actual wear profiles from the CDI model and actual plant measurements are presented in Figure 4 (next page). The model predictions were presented ahead of their implementation and again show a good degree of accuracy. Figure 3 (previous page) also predicted an improvement in throughput rate and a corresponding reduction in specific power consumption for the CDI 7 design.

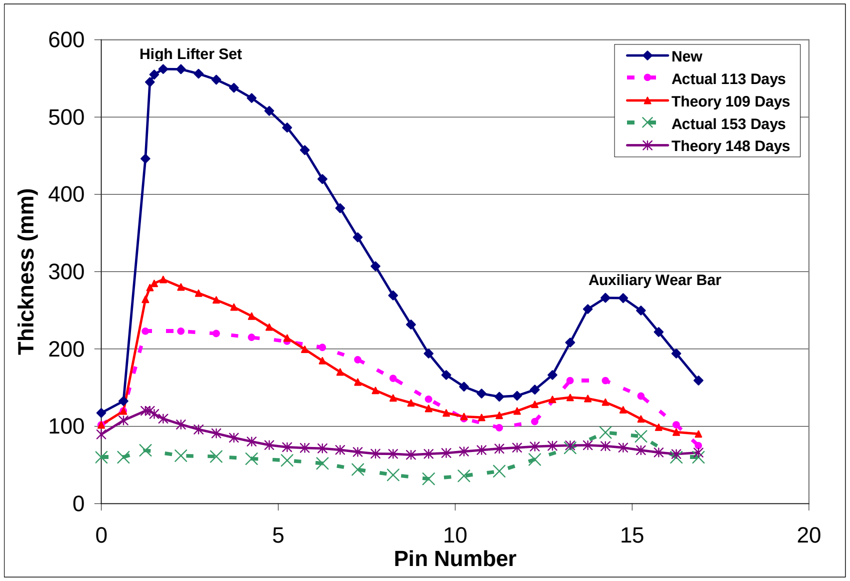

Figure 4: CDI-7 High Lifter Profile – Wear Prediction versus Measured Wear

DEVELOPMENT OF TRIAL CASTINGS

The modeling work was completed in April 2002 (8 months after the project commenced). At that time, CDI and Cadia entered in to discussions with Bradken to develop the CDI 7 design into a set of trial castings. Given the nature of the trial (no guarantee of future orders), the agreement was drafted with the following provisions;

- 12 Rows of the trial castings were to be installed in the mill with four rows placed on one side and another eight diagonally opposite to receive the charge throw.
- The liner handler lift capacity of 3.5 tonnes was not to be exceeded.
- Finite Element Analysis (FEA) was to be conducted on the bolting arrangement to ensure their integrity.
- A confidentiality agreement was to be signed by all parties protecting CDI's intellectual property.
- The cost of pattern development and future castings was to be provided up front.
- Bradken were to conduct full 3D Computer Aided Design (CAD) modeling to ensure the design was suitable for manufacture, bolting and installation.

- Casting drawings were to be signed off by CVO prior to fabrication.
- Pattern modification costs were to be "shared" if the trial was deemed to be unsuccessful or met by Bradken over the exclusive supply of 6 full sets if the trial was successful.

The 12 rows of trial castings were delivered in preparation for a shutdown in December 2002 and installed at that time. Figure 5 shows in cross section the profile of the new liner design compared to the then current CVO design.

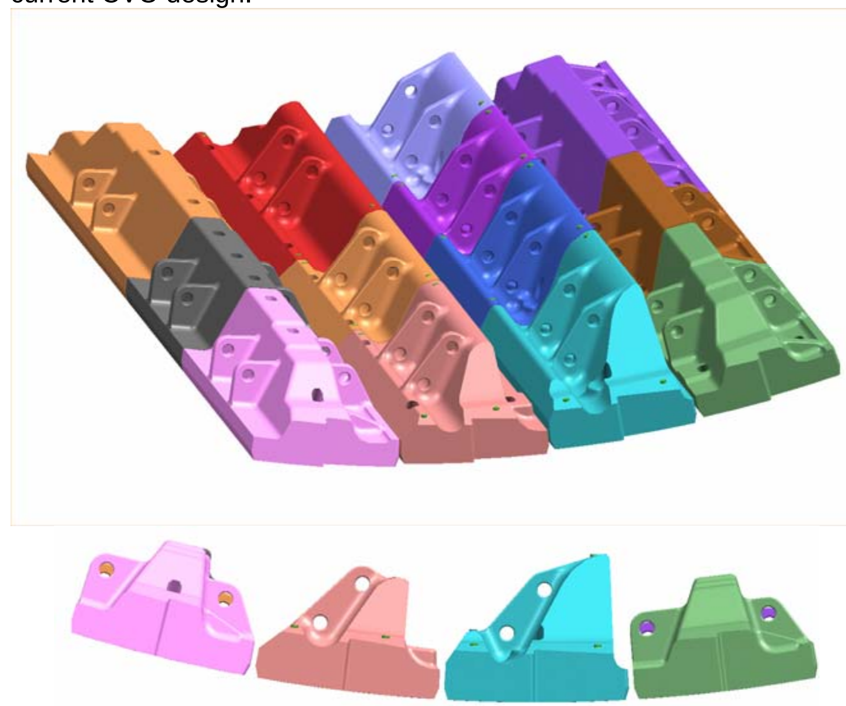

Figure 5: Trial Casting - Comparison of Current and New Liner Profiles

Features of the new design were;

- A lifter face angle of 28 degrees, tapering towards the top of the lifter in order to reduce overthrow of balls on start up.
- A high lifter of 422mm above the plate
- A medium lifter of 300mm above the plate
- A mini-lifter of 90mm above the plate on the leading edge of each casting to reduce wash at the end of the lifter life

- Plate thickness of 145mm on the lead side of the lifter and 115mm on the lag side of the lifter.

In order to maintain the weight of castings within the specified 3.5 tonne maximum liner handler limit, the high discharge end lifter had to be cast in two pieces, with the resultant disadvantage of increased relining time. Although not desirable this was considered a reasonable compromise rather than reducing the liner mass below the preferred design. Subsequent to this liner handler capacity has been increased through the purchase of a 6 tonne capacity machine (Weidenbach et al, 2006). Figure 6 shows one of the castings.

Figure 6: Example of the Trial Casting Prior to Installation

TRIAL OF A NEW SHELL LINER DESIGN

The purpose of the trial was to establish whether the liners would survive in the mill. Impact on the opposite side of the mill (charge toe) had the potential to cause damage to the casting, due to the higher lifter height throwing the charge too far, although DEM modeling suggested otherwise. It was also necessary to confirm how much longer the new profile castings would last, as a result of the design changes, and it gave an important opportunity to assess the design profile and determine

whether any modifications would be required before changing out the entire mill shell.

The trial liners (12 out of 52 rows) were installed with set number 12 in December 2002 and no fitment issues arose during the installation. Figure 7 shows the first trial liners being installed.

Figure 7: Trial castings installed in the 40 foot Diameter SAG Mill

Following a mill inspection in January 2003 (4 weeks into operation) the trial was deemed to be sufficiently successful to allow an order to be placed for the next scheduled reline (April 2003).

The main issue to be highlighted during the trial was that balls became jammed in between the high and mini lifters. This was a critical issue that had to be addressed prior to the first full shell installation, in order to allow safe entry in to the mill. To resolve this issue the angle of the mini lifter was laid back further to ensure that balls would not become stuck in the cavity.

At the time of the trial liner set 12 removal (April 2003) there was up to 100mm more metal left on the CDI liners compared with the then current CVO / Bradken design, this confirmed that the liners would last significantly longer (potentially up to 30 days).

PERFORMANCE TO DATE

The first full set of CDI design shell liners were installed in the mill in April 2003 (set 13). Table 3 shows key operational data over the last 8 years of production at CVO and forms the basis of the comparison between the CVO / Bradken design efforts and the CDI-7 liner design improvement.

Table 3: Summary of Key Operational Parameters

Set	Date Installed	New Feed Tonnes (Mt)	Total Feed Tonnes (Mt)	No. of Days	Liner Type and Conditions
1	**Jun 98**	**6.25**	**n/a**	**142**	**78 Row Hi:Lo**
2	**Dec98**	**7.26**	**8.50**	**154**	**52 Row Design Operating in Bi-directional Rotation**
3	**Jun 99**	**6.37**	**7.53**	**139**	
4	**Nov 99**	**8.11**	**10.28**	**169**	
5	**May 00**	**6.98**	**8.60**	**139**	
6	**Oct 00**	**6.30**	**8.31**	**129**	
7	**Feb 01**	**6.44**	**8.26**	**132**	
8	**Jul 01**	**5.86**	**7.62**	**117**	**52 Row Design Modified For Single Direction**
9	**Nov 01**	**6.00**	**7.76**	**116**	
10	**Mar 02**	**6.26**	**8.55**	**128**	
11	**Aug 02**	**5.62**	**7.56**	**115**	
12	**Dec-02**	**5.82**	**7.40**	**113**	
13	**Apr-03**	**7.26**	**9.73**	**143**	**52 Row CDI Shell Design Operated in Single Direction**
14	**Sep-03**	**7.84**	**10.42**	**158**	
15	**Feb04**	**6.496**	**8.36**	**131**	
16	**Jul-04**	**6.08**	**7.77**	**124**	
17	**Nov-04**	**6.32**	**8.24**	**129**	
18	**Apr-05**	**6.26**	**8.06**	**133**	
19	**Sep-05**	**6.44**	**7.99**	**135**	

New feed as well as Total feed (which includes recirculating load of crushed pebbles) was included in the analysis as both had the potential to drive liner life and mill efficiency.

As with many such comparisons carried out over such a long period of time there have been a number of operational changes made during the last 8 years which complicate the data analysis. These include;

- A gradual increase in SAG mill ball charge level from 12% up to 15% in the first 2 years of operation.
- Operation of the concentrator with up to 7% pre-crushed feed (during the ramp up of Ridgeway underground mining operations between November 1999 and April 2003) and;

- Finer fragmentation due to increased powder factor used in the mine from December 2002 and a gradual coarsening since November 2004 as the powder factors were again reduced.
- Processing ore from a satellite pit “Cadia Extended”.

The CDI-7 liners resulted in an immediate increase in life from 115 days to 143 days, a 24% improvement on the recent historical performance in single direction (CDI prediction 20%). This had been achieved with a corresponding increase in liner mass of 12% compared to the corresponding single direction design.

Comparing the last 3 “conventional” design liners with the first 3 “CDI-7” design liners gave an indication of the throughput gains made with the new design. Allowing for the finer SAG mill feed presented in sets 10 to 12 (due to the treatment of Ridgeway ore) the “corrected” throughput was 2040tph. This compares with an average throughput for the first 3 CDI liner sets of 2080tph, a gain of about 2% (CDI prediction 6%).

Due to the complexity of changes over this period of time and uncertainty in the contribution of each factor to the overall result it was agreed to judge the success of the liners in terms of overall life and total tonnes ground.

As a result of the extended life, the average total throughput for a set of shell liners rose from 7.8Mt to 8.8Mt. There had, however, been a 15% increase in liner mass since that time in order to counter the accelerated rate of metal loss associated with higher throughput rates and the wearing of the liners in one direction only.

There has been a clear improvement in liner life since the CDI-7 design was installed in April 2003. The three production periods of interest have been further summarised in Table 4 below;

Table 4: Summary of Key SAG Liner Performance Periods

Period	Total Feed		New Feed		No of Days	Sp Pwr kWh/t
	Mt	tph	Mt	tph		
Bi-Direction	8.578	2494	6.909	2006	144	8.81
Bi-Dir (Cor)	**8.386**	**2434**	**6.781**	**1966**	**144**	**9.01**
Single	7.781	2748	5.910	2089	118	8.63
Single (Cor)	**7.522**	**2656**	**5.737**	**2028**	**118**	**8.92**
Single CDI	**8.791**	**2646**	**6.769**	**2040**	**138**	**8.69**

Corrected results (allowing for Ridgeway fine feed) can be compared directly with the Single direction CDI period. The single direction production period with CDI based design liners now closely matches the total throughput and liner life achieved in bi-direction rotation.

The throughput rate of new feed (4% higher) and total feed (including recycle pebbles 9% higher) suggests that significant changes have resulted from the change to single direction mill rotation for the Cadia Hill SAG mill. Although difficult to compare the 2 single direction operating periods directly, allowing for the finer Ridgeway ore feed suggests that a throughput benefit of 12tph has resulted from the change (with a slight reduction 9tph in the total feed rate). Specific power consumption has reduced by between 3 and 5% as a result of the change to CDI-7 liners.

BENEFIT OF SINGLE DIRECTION ROTATION

In order to determine whether it was cost effective to retain the single direction mill rotation a cost benefit analysis was conducted (Table 5). Although more expensive operating costs are incurred, this is offset by increased production rates from the mill as a result of improved pebble removal efficiencies. The overall result of this analysis was in favour of the single direction mill rotation.

Table 5: Single Direction versus Bi-Direction Rotation Evaluation

Parameter	**Bi-Direction**	**Single Direction**	**Variance**
SAG Shell			
Cost of liners $/set	$1.24M	$1.54M	$0.30M
Shell relines No./a	2.54	2.68	+0.14
Total Shell $/a	$3.15M	$4.13M	$0.99M
Shell reline hrs/a	139.2	147.4	+8.3
SAG Pulp Lifters			
Cost of Liners	$0.30M	$0.40M	$0.10M
Pulp Lifter relines/a	1.1	0.4	0.4
Total Pulp Lifter/a	$0.33M	$0.16M	-$0.16M
Pulp Lifter reline h/a	12.4	4.6	-7.9
Operation Data			
Throughput tph	2006	2040	+34

This improvement has been driven by more efficient pebble removal from the SAG mill which results in a greater recycle load (and hence total

throughput). This is supported by the 6% increase in total feed (new feed plus recycle load) and only a 2% increase in new feed rate since the move to single direction rotation.

- There was an increase in SAG mill shell liner cost of $0.99M/a
- There was an increase in SAG shell reline time of 8.3 hours/a
- The curved discharge end resulted in pulp lifter change out cost reductions of $0.16M/a
- Pulp lifter reline times have reduced by 7.9 hours, offsetting the additional shell reline time.
- SAG mill throughput has increased by 34tph, which results in a net revenues of $4.5M/a.

FUTURE DEVELOPMENT

Improvements have been made to the shell liners that have returned the life and tonnage milled by each set to the levels obtained with bi-direction mill rotation. CVO are keen to progress further advances and whilst in the short term are looking to optimise the size and number of the current CDI liners installed in the mill future work will also involve;

- A possible move to 39 rows of lifters.
- Evaluation of the bolting arrangements to reduce the number of bolts removed and replaced on each liner.
- Move away from liners bolted through the plate as the 2 sets of bolts set up localized stresses (particularly if the backing rubber is not cleaned properly). The liners bolted in this manner occasionally crack along their length. The pieces are well held though and do not impact on production downtime.

CDI have proposed two further profiles which may take the comminution rates to a new level. These are under consideration for future plant trials. The CDI-8 design is a more “conventional” option, while the others would appear to be more radical in their approach.

Figure 8 (next page) illustrates the predicted comminution performance of the CDI-8 design. Throughput rates and liner life may be increased by a further 5% compared with the CDI-7 design. Power consumption is also expected to reduce as a result of this new design (Figure 9, next page).

CONCLUSIONS AND RECOMMENDATIONS

The change to single direction mill rotation resulted in a reduction in life of the shell liners of 15%.

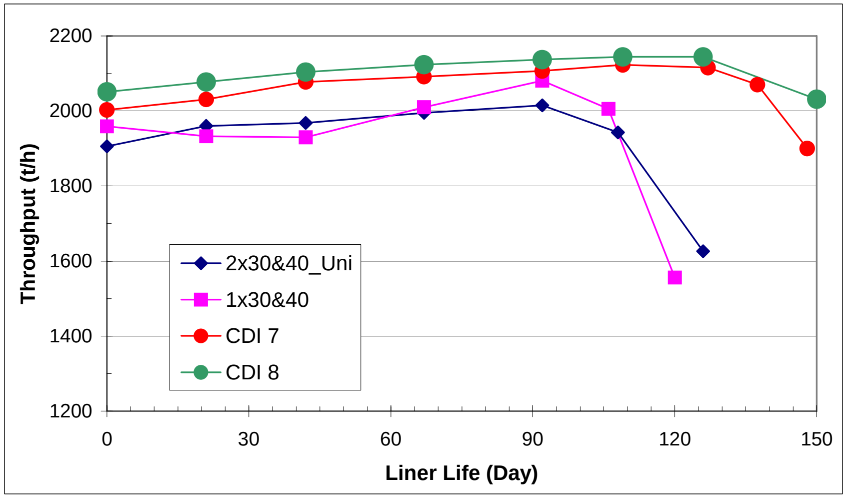

Figure 8: Throughput vs Liner Life Predictions for CDI 8 Design Profile

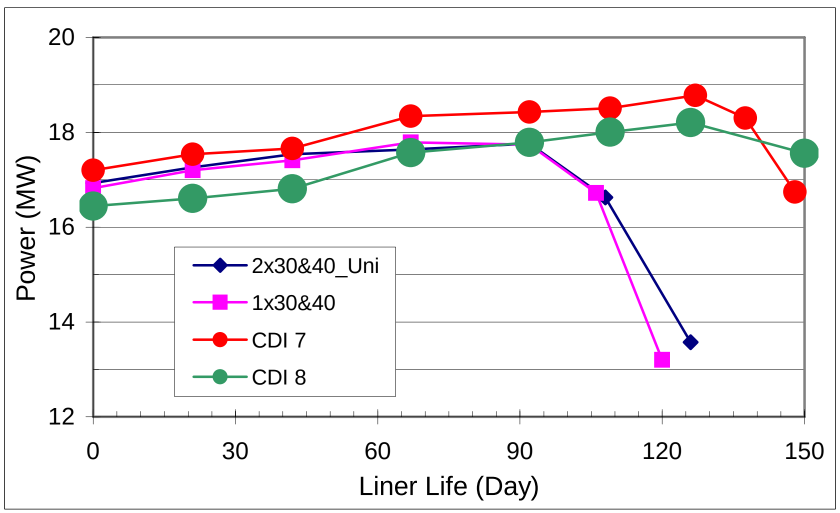

Figure 9: Power vs Liner Life Predictions for CDI 8 Design Profile

This has been recovered through the implementation of a design developed by CDI through comminution and wear rate DEM modeling. The SAG Mill shell liner life has now returned to previous levels.

The new liner design lasted 24% longer, with an increase in mass of just 12% compared with the CVO/Bradken design. This suggests an improvement in comminution and wear efficiency has resulted.

The decision to change to single direction mill rotation has increased annual revenue for the operation.

Although more costly to install the CDI liners, the benefit of additional throughput and similar operating time justifies this decision.

Comparing single versus bi-direction rotation overall plant downtime was neutral with the additional shell reline time offset by fewer pulp lifter change outs. The real benefit has resulted from an improvement in the overall plant throughput rate.

The wear models have predicted wear life very well for the new design installed at CVO. This provides confidence in taking the next step forward for the Cadia SAG Mill.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the input of their colleagues who have worked on developing the liner designs at CVO over the last 8 years, as well as Newcrest Mining Pty. Ltd., Bradken resources and Conveyor Dynamics, Inc. for permission to publish this paper.

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