IMPROVING ENERGY EFFICIENCY VIA OPTIMIZED CHARGE MOTION AND SLURRY FLOW IN PLANT SCALE SAG MILLS

FINAL TECHNICAL REPORT

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ABSTRACT

A research team from the University of Utah is working to make inroads into saving energy in these SAG mills. In 2003, Industries of the Future Program of the Department of Energy tasked the University of Utah team to build a partnership between the University and the mining industry for the specific purpose of reducing energy consumption in SAG mills. A partnership was formed with Cortez Gold Mines, Outokumpu Technology, Kennecott Utah Copper Corporation, and Process Engineering Resources Inc. At Cortez Gold Operations the shell and pulp lifters of the semiautogenous grinding mill was redesigned. The redesigned shell lifter has been in operation for over three years and the redesigned pulp lifter has been in operation for over nine months now. This report summarizes the dramatic reductions in energy consumption. Even though the energy reductions are very large, it is safe to say that a 20% minimum reduction would be achieved in any future installations of this technology.

EXECUTIVE SUMMARY

In the current project, Cortez Gold Mines played a key role in facilitating the 26-ft SAG mill at Cortez as a test mill for this study. According to plant personnel, there were a number of unscheduled shut downs to repair broken liners and the mill throughput fluctuated depending on ore type. The University team had two software codes, Millsoft™ and FlowMod™ to tackle the problem. Millsoft™ is capable of simulating the motion of charge in the mill. FlowMod™ calculates the slurry flow through the grate and pulp lifters. Based on this data the two models were fine-tuned to fit the Cortez SAG will.

In the summer of 2004 a new design of shell lifters was presented to Cortez and in September 2004 these lifters were installed in the SAG mill. By December 2004 Cortez Mines realized that the SAG mill is drawing approximately 236-kW less power than before while maintaining the same level of production.

In the first month there was extreme cycling and operators had to learn more. However, the power consumption is 0.3-1.3 kWh / ton lower than before. The actual SAG mill power draw is 230-370 kW lower. Mill runs 1 rpm lesser in speed on the average. The re-circulation to the cone crusher is reduced by 1-10%, which means more efficient grinding of critical size material is taking place in the mill. On average the plant operating work index decreased by 1.2 kWh/ton milled over 2 sets of the new shell liner design. The SAG power draw has been reduced 94-262 kW (126-351 HP) with the new shell liner design. This was due to the SAG mill grinding more efficiently with optimized ball strikes and feeding a better product to the ball mill circuit, while yielding essentially the same average throughput before and after the design change. All of the savings have resulted in reduction of operating cost of $0.023-$0.048/ ton.

After completing the shell lifter design, the pulp lifter design was taken up. Through a series of mill surveys and model calculations it was figured that the radial pulp lifter installed on the mill had less than optimum discharge capacity. A number of alternative designs were evaluated. The final choice was the Turbo Pulp Lifter for which Outukumpu Technology, Centennial, Colorado had filed a patent. After installation of the pulp lifter a 22% increase in throughput rate

from 344 stph to 421 stph was realized. A 35% decrease in the SAG mill power draw from 3,908 HP to 2,526 HP (2,915 kW to 1,884 kW) was recorded. This equates to a 47% decrease in SAG unit energy consumption from 8.98 kWh/ton to 4.74 kWh/ton. A 11% decrease in SAG mill speed was observed indicating optimized ball strikes. Also, the ball chip generation from the SAG mill was reduced considerably. Further more, a 7% decrease in ball mill power draw from 4,843 HP to 4,491 HP (3,613 kW to 3,350 kW) was observed. This equates to a 24% decrease in ball mill unit energy consumption from 11.13 kWh/ton to 8.43 kWh/ton.

The design of shell lifters and pulp lifters far exceeded expectations. Based on data collected over 90 days after pulp lifter installation, it is projected that Cortez Gold Mines would save 742,320 kWh or $67,000 in SAG mill electrical savings. In the ball milling circuit a saving of 181,786 kWh or $17,100 electrical savings. The increased production of 77 stph translates to 4,000 ounces of incremental gold production. This amounts to $2.4M incremental revenue increase per month at a gold price of $600 per ounce.

The US mining industry operates approximately 80 semi-autogenous grinding mill around the country including Alaska. These mills are primarily in use at copper, iron, gold, silver and zinc mining operations. The total installed power of these SAG mills is estimated at 350 MW. The study done at Cortez Gold Mine shows that considerable energy savings is achieved in the semi-autogenous mill and as a consequence of optimized operation of the SAG mill energy savings is realized in the subsequent ball mill operation also. Hence, it is concluded that the shell and pulp lifter technology detailed in this report would save a minimum of 20% energy in any future large SAG mill application. At a installed power of 350 MW around the country, operation for one hour consumes 350 MWh of electricity. At a saving of 20% this technology reduces the energy consumption by 70MWh in all mining operations combined.

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1. INTRODUCTION

Cortez Gold Mines commenced operation in 1969 Mill #2, commissioned by mid-1997, was a nominal 10,000 tons per day SABC circuit followed by an 8-stage CIL circuit for oxide gold ore. A simplified flow sheet of the current mill is shown in Figure 1.
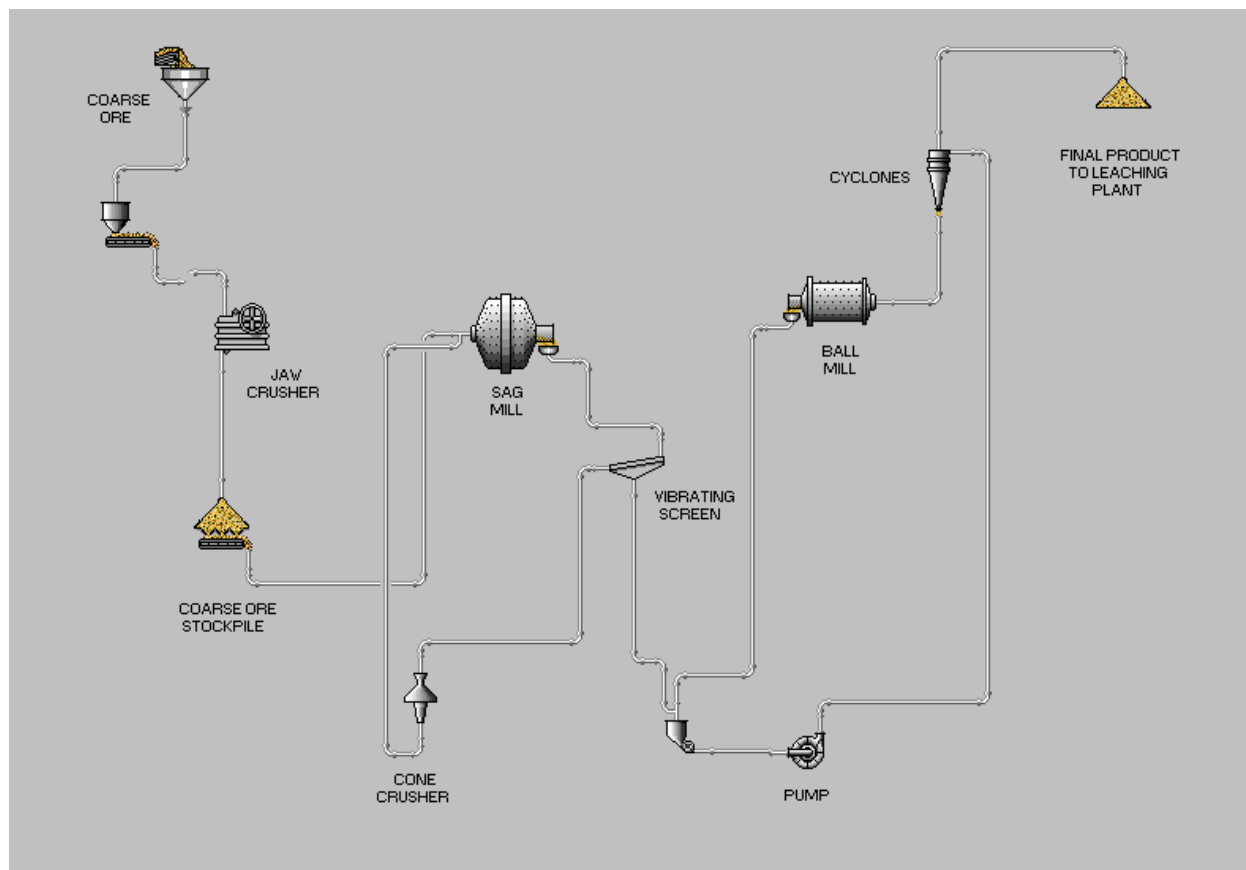
Figure 1

Figure 1: Cortez Gold Mines Mill #2 Flowsheet

The SAG mill is 26 ft in diameter and 12.25 ft effective grinding length and powered by 4,500 HP motor driven by a variable speed drive that can control the mill speed from 36% to 80% of critical speed depending on ore type and operational demands. Ball charge is typically 8-12%. Total mill filling is about 25%. The mill lining originally consisted of rubber plates and "polymet" lifters on the feed and discharge ends as well as rubber plates and cast lifters on the mill shell. The shell lifter pattern was 52 rows of high-low pattern (nominal 7 inch lift followed by 5 inch lift above shell plate) built with a 17° face angle. The grate open area was nominal 7% generated from 2.75 inch x 2.75 inch square holes. 5 inch grinding balls are also used. The

maximum grinding circuit throughput as dictated by downstream conditions is about 13,500 dry tons per day (560 dtph).

Early in the Mill #2 life the ore had been predominantly ball mill limiting in that the ore basically passed through the SAG mill due to its already small size. Regardless of this, budget throughput targets that surpassed the original plant design figures were consistently being met. Therefore, improving SAG mill performance has been limited to liner wear life optimization. As Cortez progressively mined deeper into the pit in 2003 and early 2004 the ore generated a steadily increasing plant operating work index. The harder ore in turn started to move the plant towards SAG mill limiting operation. Slowly target capacity was just barely being met or just falling under targets. This issue was also being compounded by shell liner repair downtime induced by the aggressive ore. The ore was causing less wear material life in upstream crusher linings.

The University of Utah approached Cortez in March, 2003 for participation in the U.S. Department of Energy (DOE) project. The primary tools that were used in this project were the MillSoft™ and FlowMod™ software packages. In the initial stages of the project it soon became readily apparent that significant opportunities existed to improve on mill operating energy efficiency as well as improve on liner profile for improved productivity. This DOE study helped identify significant SAG circuit bottlenecks that should be addressed to maximize the current installed circuit as well as the possible future mill expansion to 15,000 tons per day.

2. SAG MILL CRASH STOPS

After the project was approved baseline data collection was required in the form of SAG mill "crash stops". In a crash stop the SAG mill is operated under steady-state conditions and then stopped. The stopping is very sudden. The ore belt and water flow to the mill are stopped and the mill power switch is immediately turned off. After mill lock-out and confined space procedures are satisfied researchers enter the mill discharge trunnion and take measurements and pictures of mill filling, ball load, slurry pooling, and liner wear observations. The line wear observation includes profiling the liner surface with a rubber clad steel tape and copying the profile on paper. The mill is then restarted and then let to continue production. Sometimes, the mill charge is ground out without further ore feed for further ball charge and liner measurements. Cortez Management, Safety, Electrical, Mill Maintenance, and Mill Operation departments were coordinated, during crash-stop procedures.

2.1 Crash Stop #1 – October 8, 2003

Figure 2 shows the accumulated slurry, rocks and balls in the mill upon entry during the crash stop. This crash stop was done on moderately ball mill limiting ore that typically averaged 460 dry tph. The picture does suggest some slurry pooling as well as some packing between lifters. The measured mill filling was 25% with a 10% ball load. The lifters also showed some peening due to ball overthrow beyond the charge toe onto the unprotected shell lifters.

Figure 2: SAG Mill Crash Stop on 10/8/2003

2.2 Crash Stop #2 – March 3, 2004

This crash stop was done on severely SAG mill limiting ore that typically averaged 360-390 dry tph. In comparison, the worst case SAG mill limiting ore type throughput is 8,160 dry tons per day (340 dtph). Figure 3 shows severe slurry pooling in the mill indicating that during operation with such hard ores the slurry and pebbles are retained in the mill. As shown in Figure 4, lifter peening and cracking was visibly extensive in many areas of the mill. Figure 5 shows completely missing lifter segments.

Figure 3: SAG Mill Limited Ore Lifter Packing on 3/3/2003

Figure 4: Lifter Peening From Ball Charge Overthrow
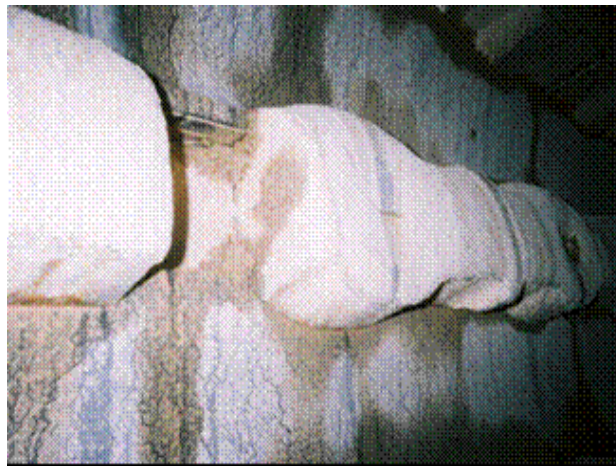
Figure 5: Broken lifters from Charge Overthrow

2.3 Crash Stop #3 – June 30, 2004

The purpose of this crash stop was to investigate the possibility of increasing mill production beyond the nominal 10,000 tons/ day operation. This size distribution data around the SAG mill was collected for another Cortez internal project. However, the major details were made available to the DOE project. A full grind circuit survey, including feed belt cut, crash stop, and grind-out were done to gather all relevant data. The moderately SAG mill limiting ore throughput was 420 dtph. Figures 6 and 7 show the slurry pooling inside the SAG mill.
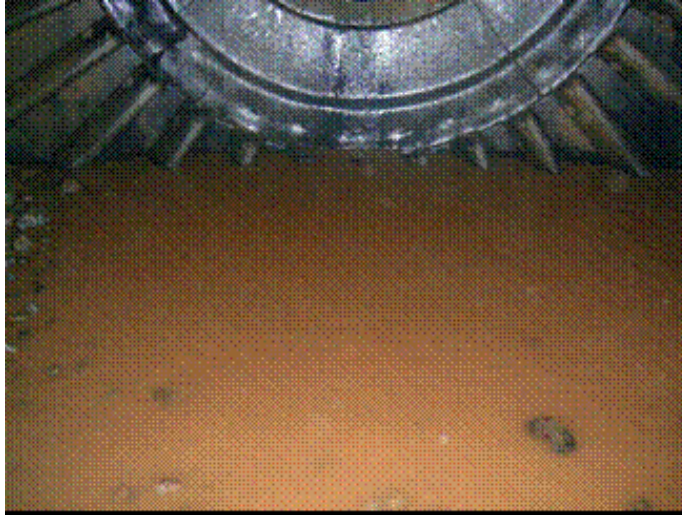
Figure 6: Slurry Pooling with SAG Mill Limited Ore on 6/30/04

Figure 7: Slurry Pooling and Lifter Packing with SAG Mill Limited Ore on 6/30/04

2.4 Review of Crash Stop Results

Crash stop data pointed out to a number observations:

- The lifter spacing is too close. They pack easily with ore and the effective lift and mill volume is reduced. This would suggest that less of the available mill power can be used for grinding.
- The lifter face angle is too steep such that high mill speed required for harder ore result in balls overthrowing the toe of the charge and striking the unprotected mill shell liners. Hence, a portion of the applied mill power is wasted turning the mill faster to grind the

harder ore as well as the subsequent unnecessary and costly liner breakage and mill downtime.

- The mill is not adequately discharging the ground slurry. In essence the pulp lifter is returning the slurry back into the mill. This means that the mill volume is taken up by material that is already product sized.
- The slurry pool could dampens ball-to-charge impacts and therefore wastes a portion of the applied mill power by "grinding water" and/or re-grinding product sized ore.

These considerations led to computer simulations to find solutions to "broken lifters" and "slurry pooling problems.

2.5 Computer Simulation of Crash Stop Results

The crash stop measurements, liner profiles, operator observations, and recorded PLC data were then processed in Autocad software package. The software outputs are depicted in Figures 8-10. The figures illustrate that with packed lifters, the worst case lift is 2 inches with the concurrent reduction in effective mill diameter of 4 inches. In addition, the MillSoft™ simulation shows that with a 17° lifter face angle lifter the media hits the unprotected shell at mill speeds of 10.5 to 11.5 rpm required to process the harder ore.
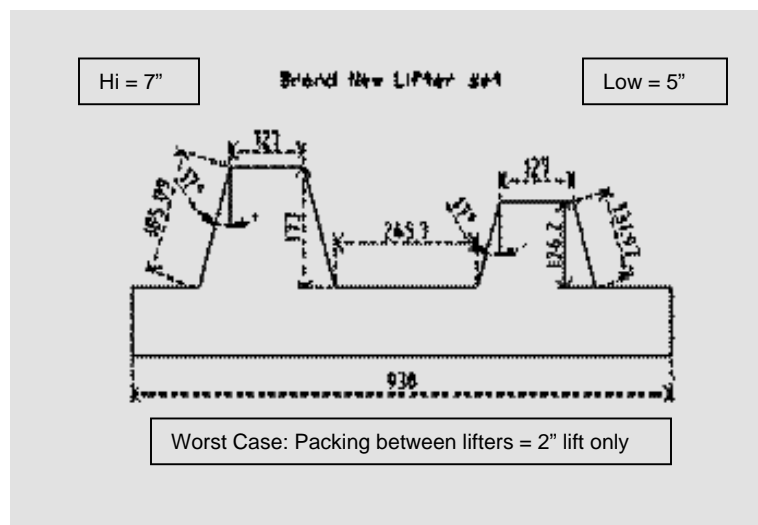
Figure 8: New Lifter Set with Packing

(Rajamani and Latchireddi, 2003)
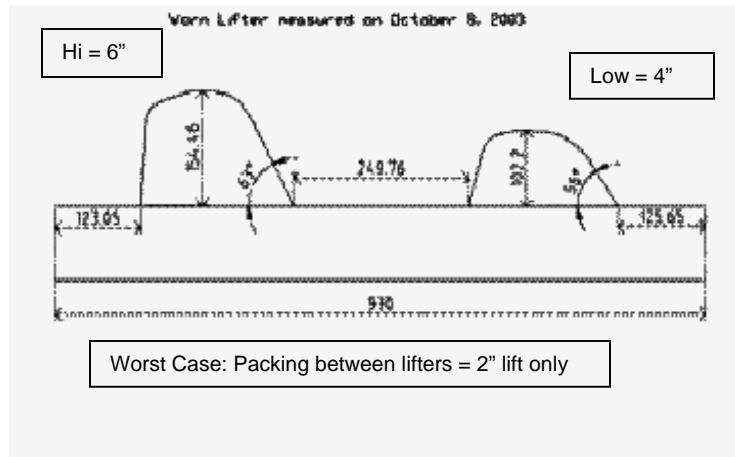
Figure 9: Worn Lifter Set with Packing
(Rajamani and Latchireddi, 2003)
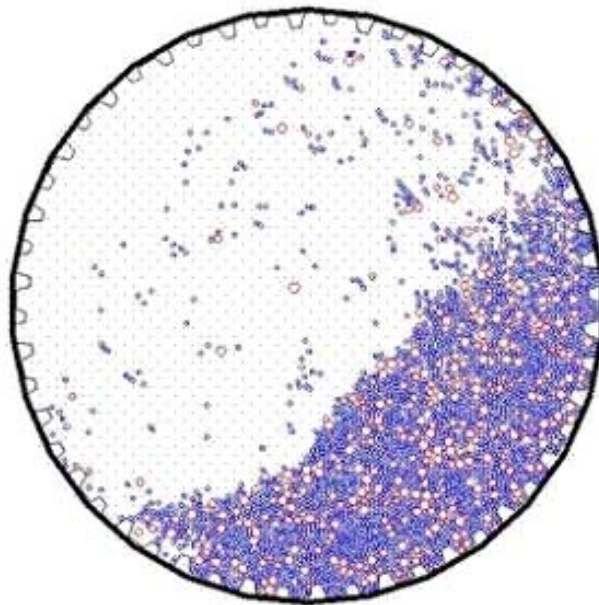
Figure 10: Charge Motion Analysis of 17° Face Angle Lifters

3 SHELL LINER DESIGN CHANGE

The above crash stops and Millsoft[TM] computer modeling showed that Cortez needed to redesign shell and pulp lifters before, mill throughput before unit energy consumption further deteriorated. Figures 11-13 show the computer simulation done with Millsoft[TM] trials at 28°, 32°, and 35° face angles, respectively.
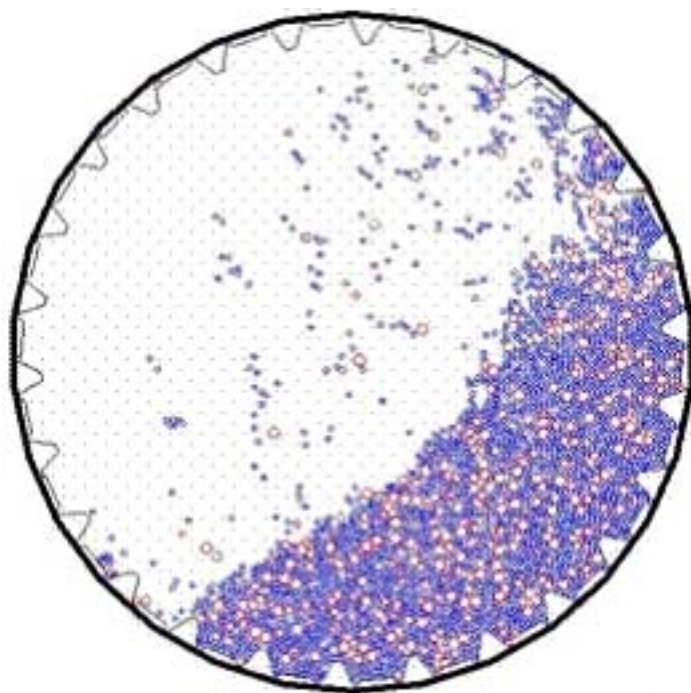
Figure 11: Charge Motion Analysis of 28° Face Angle Lifters
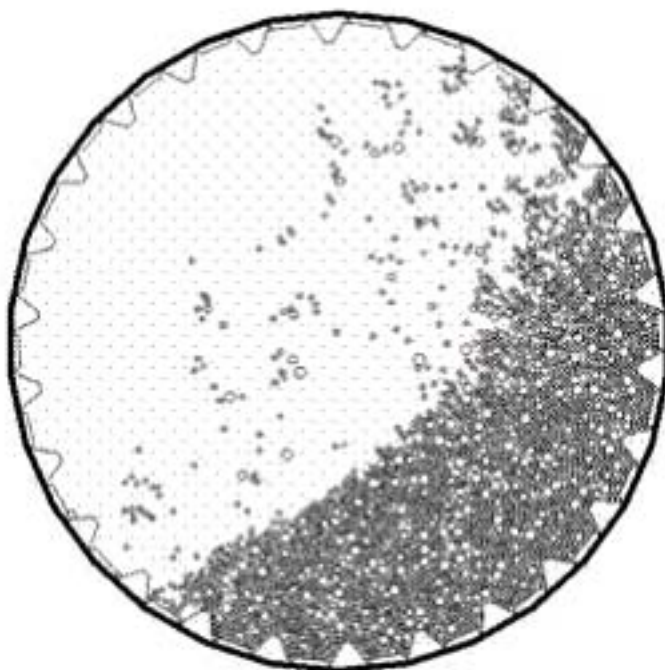
Figure 12: Charge Motion Analysis of 32° Face Angle Lifters
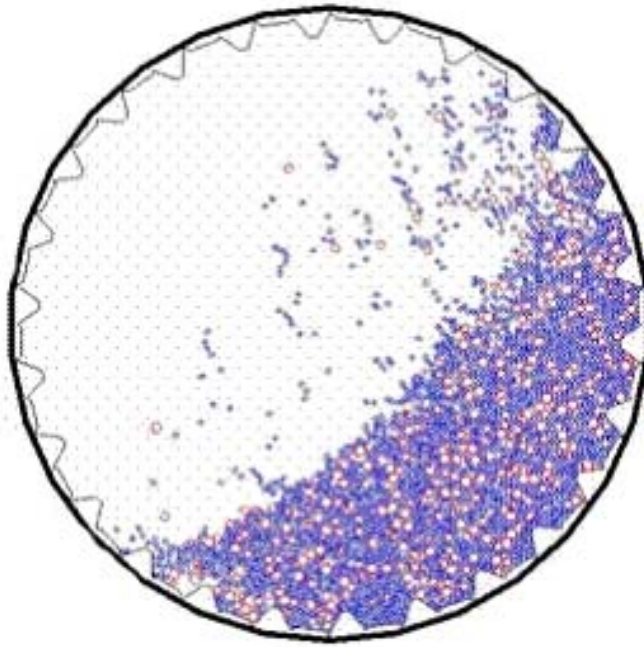
Figure 13: Charge Motion Analysis of 35° Face Angle Lifters

The 32° lifter was the starting point of optimized ball strikes at high mill speeds. Simulations clearly showed that 32° relief angle is ideal for the 24 ft. In the end, however, Cortez Management was keen on maximizing wear life even with the greater relief angle. Therefore, a 28° face angle lifter design was chosen. Needless to say the 28° angle will wear to a 32° angle over a few months. Lift height was also set at 9 inches above the 4 inches shell plate. Figures 14-15 shows the final design of the shell lifters.

9" lift
28° face angle
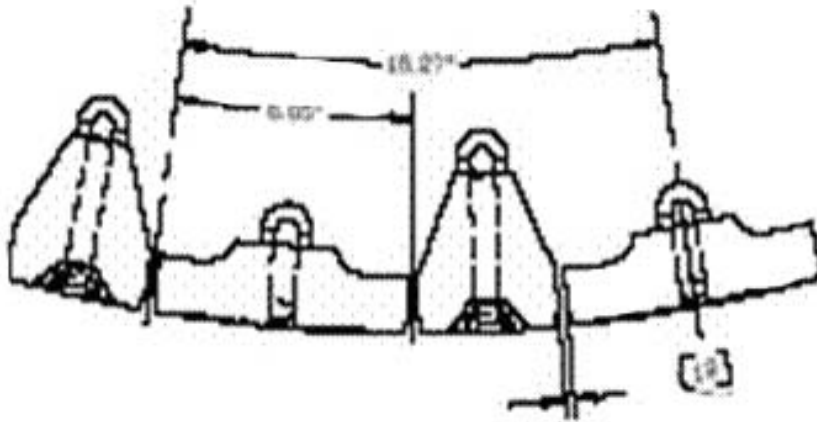
Ref: Norcast 3/26/04

Figure 14: Revised Shell Liner Design Side Profile

Retained OEM shell plate thickness

Ref: Norcast 3/26/04
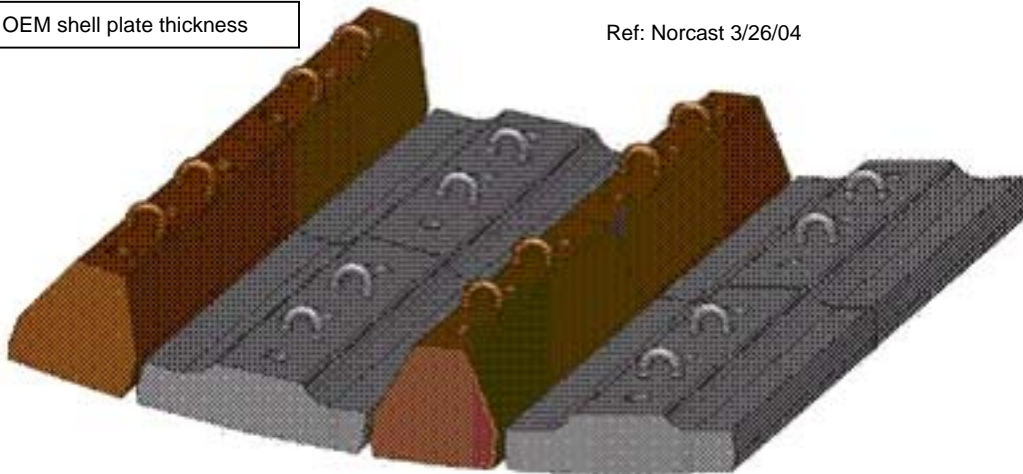
Figure 15: Revised Shell Liner Design Isometric View

4. LINER DESIGN CHANGE CONSIDERATIONS

Concurrent to this major liner design change, there were many issues in that needed to be resolved before the design could be implemented.

4.1 Safety in handling heavier cast liners:

The issue was that while the new design had 33% less pieces, each piece now weighed up to 2.5 times more than the old design. The maximum weight to be encountered was 2,000 lbs. Therefore, the existing liner handler was sent it to the manufacturer to be upgraded and professionally recertified from 3,000 lbs capacity to 4,000 lbs capacity. In addition, numerous pre-installation meetings involving the mill maintenance, operations, safety, and management departments as well as the liner manufacturer were held to break down the liner change step-by-step. These meetings ensured adequate equipment and procedures were available. With all of the above covered, Cortez operations felt fairly confident that they would safely handle the upcoming design change.

4.2 Noise due to cast liners in the plant

The issue was the cast liners would operate noisier than the old design rubber plate-cast lifter combination. Upon consultation with other plants about this, the response was that it was a non-issue to them because of already established hearing protection policies and that the sound was not obnoxious provided that the mill was operated properly. A post implementation survey conducted before and after noise showed that the noise only increased by 2%.

4.3 Heavier cast liner weight the mill shell and its effect on mill motor power draw

Another issue was that the new shell liner design weighed at 41 extra tons. Such a load would cause undue stress to the mill shell as well as mill motor. Calculations were also done that showed only about 100 extra HP was required to start the mill in order to overcome bearing pressure friction after which the "flywheel effect" would takes over. Actually, after the change mill starts up under a full load was easier than the previous design undoubtedly due to the flywheel effect.

4.4 Response of inching drive due to increased mill weight:

The issue of an inadequate inching drive stemmed from the ball mill inching drive. Its performance was severely hindered with a fully charged and/or frozen charge ball mill. This was also a non-issue in regards to a SAG mill because of the large diameter causing a counterweight effect balanced by the charge. The mill would be most unbalanced when half of the liner installation was complete such that jogging the mill into place would be difficult as compared to inching it into place. The SAG inching drive did work hardest at this point, but nowhere near the difficulty the ball mill inching drive had on the ball mill under similar circumstances.

4.5 Effect on operating practice change with the new liners:

The concern was that the expensive set of new liners would be damaged upon start-up due to operator unfamiliarity running with new mill speed and bearing pressure targets that would be undefined until some experience is gained. The resolution was to discuss these concerns with all the operators beforehand and then practice conservatism on mill speed and aggressiveness on mill bearing pressure upon new liner commissioning. In addition, the operators were given explicit instructions to run the mill under their control rather than Expert System control to learn the new operating regime.

5. SHELL LINER DESIGN CHANGE OPERATING RESULTS

The new design encountered numerous different ore types over its life similar to the previous design's life such that one could come to some valid conclusions. Without extensive work index and mineralogy data, the derived conclusions focus on what the operating data clearly shows:

- **Similar mill throughput.** Before the change the mill averaged 411 dtph and after the change it averaged 419 dtph on the first shell liner set. On the second shell liner set the averaged 400 dtph. Essentially the throughput has been similar due to our variability.
- **Overall reduced unit energy consumption on both mills**. On average the plant operating work index decreased by 1.2 kWh/ton milled over 2 sets of the new shell liner design. The SAG power draw has been reduced 94-262 kW (126-351 HP) with the new shell liner design. This was due to the SAG grinding more efficiently with optimized ball strikes and feeding a better product to the ball mill circuit, while yielding essentially the same average throughput before and after the design change.
- **Increased use of the mill volume for grinding.** Lifter packing throughout the new shell liner design life has disappeared thereby allowing the use of the entire mill diameter for grinding.

Figure 16: No Lifter Packing with New Shell Liner Design

- **Virtually eliminated downtime from broken shell liner bolts for the first time in Mill #2 history.** Since the new design install Cortez had no downtime due to shell liner bolt problems.
- **Increased grinding of critical size material in the SAG.** The SAG now began to perform like a secondary crusher and grinding mill like a SAG mill was conceptually intended to do from its early beginnings. When Cortez started the new design on essentially the same ore type as the old design one immediately noticed less pebbles being recycled to the pebble crusher, but the cyclone feed circuit recirculating load increased with a slight decrease in grinding circuit product size that was still within metallurgical guidelines. This suggested more grinding of critical sized SAG material with the subsequent increase in particle size of typical ball mill feed.
- **Increased liner life.** Measurements and calculations done on both old and new liner designs reveal that the liner wear life has improved 47% to 57 kgs/day steel loss from the previous design's 84 kgs/day

6. EVALUATION OF SAG PULP LIFTER

The Cortez Gold Mine mill had been fitted with the new design of shell lifters, which has been in operation since September 2004. In the two years it has been in operation it became clear that the mill was not discharging the ground ore slurry efficiently. This was evidenced by a number of observations including the performance of the mill without the pebble crusher. Some mill-entry observations also showed slurry build-up known as pooling.

The new liner design emphasized the now increased importance of the pebble cone crusher in the SAG circuit. Whenever the pebble crusher was bypassed for cleaning or maintenance, an immediate drop in mill throughput on the order of 50-100 stph was noticed. Prior to the shell lifter design change, the pebble crusher had at most a 25 stph effect on mill throughput and often sat idle over all ore types. The initial thought was that when the pebble crusher was online, the SAG mill was very efficient in grinding the critical size material in the mill due to the crushed pebbles being discharged from the mill on their next pass through it. When the pebble crusher was bypassed, the effect was almost an immediate 80-100 stph increase of critical size material back into the mill thereby overloading it.

Although the pebble crusher applies more energy to the ore thus increasing the product fineness, it was determined that the SAG mill was not discharging the slurry and pebbles efficiently.

6.1 SAG mill is a grinding device as well as a pump

SAG mill is mainly thought of as a grinding mill in which ball charge, mill filling, and mill speed were maximized to ensure maximum throughput. Liner design for the SAG mill is approached more from a wear perspective rather than a metallurgical and hydraulic-flow perspective. However, upon grinding the ore to pebbles and ground pulp the mill has to perform

as an efficient pump. The grates and pulp discharger end must be designed for maximum slurry discharge out of the mill with minimal recirculation of product-sized material.

The theoretical maximum SAG discharge is dictated by a "grate-only" (GO) configuration in which the mill is open on the discharge end with no trunnion. The end is covered with grates without lifters. The maximum flow then becomes a fluid dynamics problem in which head pressure on the inside grates dictate the flow. The actual maximum SAG discharge at Cortez is dictated by the current radial pulp lifter (RPL) design. The comparison between actual and theoretical gives the pulp removal efficiency so therefore the maximum efficiency is realized by making the current design as close as possible to GO. Figure 17 illustrates this concept.
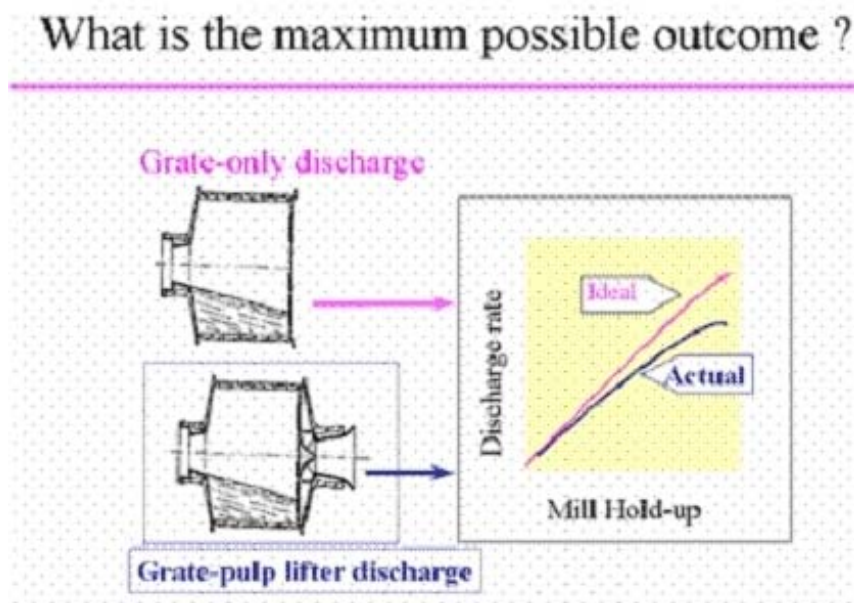
Figure 17: Theoretical Maximum SAG Mill Pulp Discharge Rate

6.2 Pulp Flow Modeling

The computer modeling of the pulp discharger was done using FlowMod™ software, that was developed by Dr. Sanjeeva Latchireddi. The model used the crash-stop/survey data collected on 6/30/04. Table 1 shows the results of model analysis. The results clearly show that at best 12,100 stpd would be realized out of the SAG mill with the current ore type. In other words, the radial pulp lifter is limiting the pebble and pulp flow out of the mill interior.

Table 1: Results of FlowMod™ Simulations on 6/30/04 Ore

Base Case 6/30/04
@ 95% Availability
@ Pebble Crusher Feed + 21% of Fresh

	Fresh Feed		Pebble Crusher	Total SAG Feed	
	dstph	dtpd	dstph	dstph	dtpd
Actual w/Radial Pulp Lifter	420	9,576	88	508	383
Theoretical Grate Only Discharge	530	12,084	111	641	482
Pulp Removal Efficiency %	---	---	---	---	79%
Max Incremental Gain	110	2,508	23	133	---

6.3 Critical Size Material Flow

The crash stop measurements, ore characteristics and mass flow measurements illustrate critical size (pebble) flow behavior with the RPL design. Essentially the critical size material was building up in the SAG mill. Especially, with the harder ore the mill rpm had to be set higher to break the ore. However, at higher rpm, the RPL pulp discharger allows slurry to be carried back into the mill, despite being discharged through the grates as shown in Figure 18.
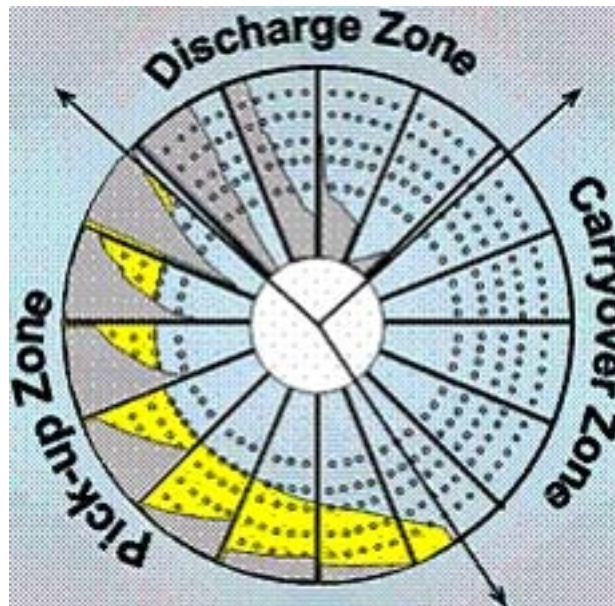
Figure 18: Pulp Discharge Profile with Radial Pulp Lifters

As the mill turns faster the critical size material then builds up even more on the interior mill circumference. The existing grate was not designed for slots towards the outer circumference. As shown in Figure 19, 12 inches of the outer mill radius was not used for pebble and pulp discharge.
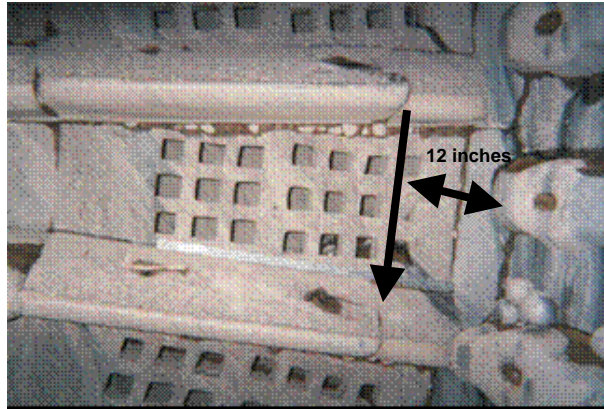
Figure 19: Unavailable Mill Diameter for Pulp and Pebble Discharge at Cortez

Hence, the lack of removal of critical size pebbles and slurry flow-back led to slurry pooling. But the level of pooling was not to the levels of traditional mill overloads. Slurry pooling causes a reduction in power draw of the mill.

The critical size material overload was further compounded when the pebble crusher was bypassed. In the SAG mill the power draw decrease and load increase happened quicker - often within 5 minutes. The only remedy was to cut throughput by as much as 100-150 stph. A sample of operating data shown in Figure 20 illustrates the reduction in throughput due to pebble crusher shut down. The subsequent drawback in addition to throughput reductions is cycling introduced in SAG throughput which in turn affects downstream mill circuits (Figure 21).
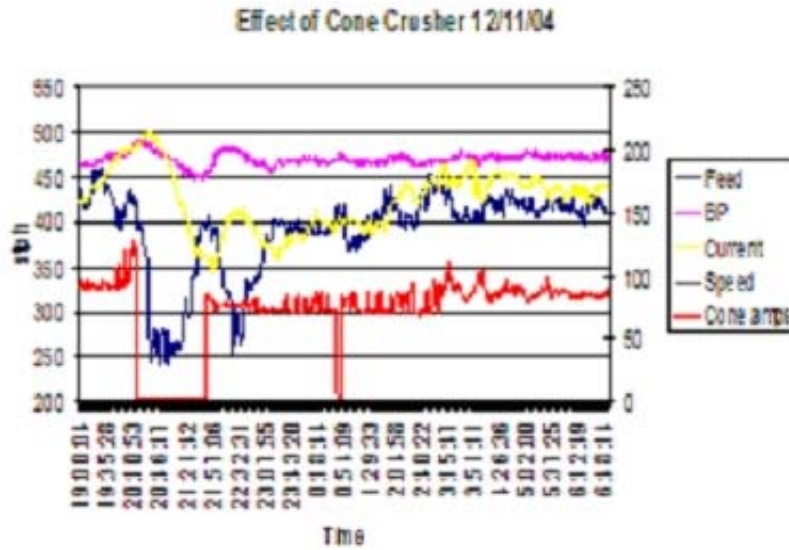
Figure 20: Effect of Pebble Crusher Bypass on Cortez SAG Performance
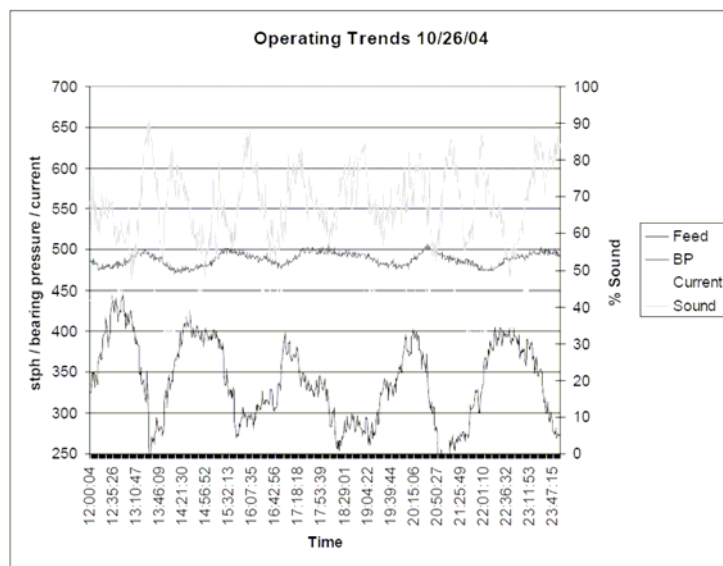
Figure 21: Cortez SAG Circuit Cycling Induced by Pebble Flow-back

The critical size recirculation within the pulp lifter was calculated to be 31%. In fact, the impact wear observed on the non-lifting side of the pulp lifter as well as on the rubber filler rings on the periphery of the mill discharge end confirmed the theoretical calculation. Minor impact wear on the Cortez SAG shell due to pebble flow-back is shown in Figure 22.

Impact wear points on all lifter blades

Impact wear points on longer lifter blades

Impact wear points on peripheral section

Impact wear point on mill shell
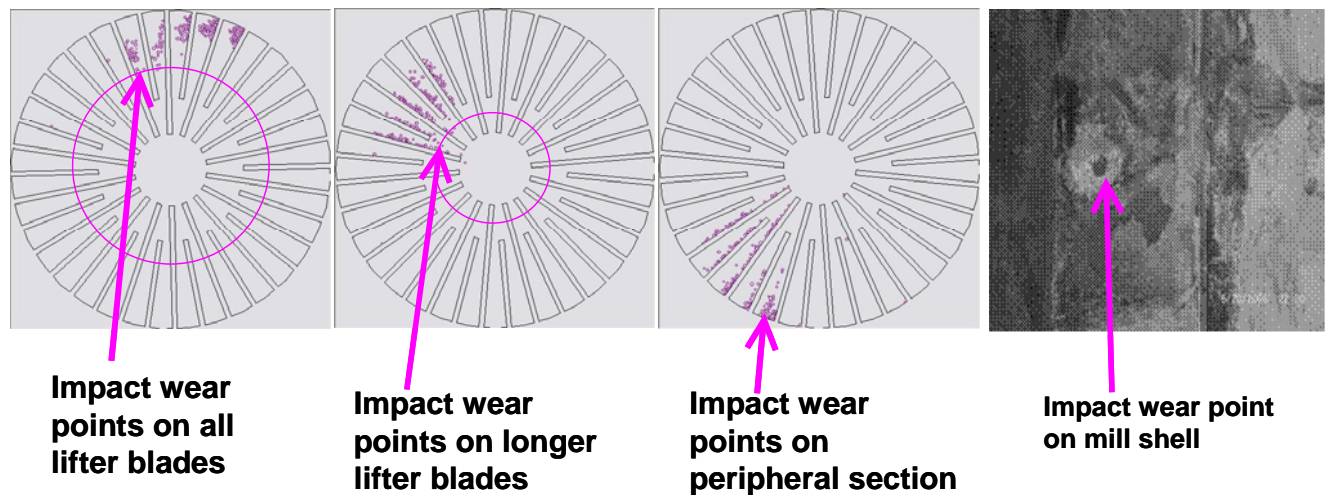
Figure 22: FlowMod™ Predicted RPL Wear Points Minor Impact Wear on Cortez SAG Shell from Pebble Flow-back

6.4 Optimized SAG Discharge End Design

The goal of the next phase of the project was to address the pulp lifters and grate open area for optimum efficiency and flow. With the aforementioned knowledge, Cortez Gold Mines decided to pursue 2nd generation of pulp lifters called Turbo Pulp Lifters (TPL™), for which Outokumpu Technology, Colorado had filed for a patent. This lifter, which is a variation of twin-chamber pulp lifter was developed specifically for AG/SAG mills with pebble circuits for efficient mill discharge (Latchireddi, 2005). The theory behind and successes of the first version called the TCPL design (Latchireddi and Morrell, 1997) are well documented (Nicoli et al., 2001).

The new design was slated to achieve the following minimum objectives:
- Minimum throughput gains on the order of 1% on the hard, blocky ores.
- A concurrent reduction in unit grinding circuit energy consumption of 0.1 kWh/ton due to reduced regrinding of product sized ore.
- Less throughput sensitivity and cycling whenever the pebble crusher is bypassed for operational maintenance..
- Increasing the shutdown interval between a complete discharge end liner changes by 1 year to every 4-5 years, as well as allowing for more even discharge end liner wear to correspond with other liner jobs.

7 INSTALLATION OF THE TURBO PULP LIFTER

Norcast Engineering Company manufactured the pulp lifter designed by Outokumpu Technology. The target date for the TPL™ installation was mid-June 2006. The overall TPL™ installation took about 4.5 days. This included 12 hours for drilling the SAG discharge head for

16 holes to complete the bolt circle pattern. Snapshots of the TPL™ are shown in Figures 23 and 24.

Figure 23: TPL™ Laid Out on Ground for Pre-Installation Review

Figure 24: TPL™ Grates on Left. OEM Grates on Right

7.1 Initial Mill Start-up on the TPL™ Design

After the TPL™ installation the SAG mill was started with the same ore that was processed immediately prior to the shutdown. This ore was also the most troublesome due to its hard, blocky nature. Following is a list observations made immediately after start up with TPL™ pulp lifter.:

- 22% increase in throughput rate from 344 stph to 421 stph.

- 35% decrease in the SAG mill power draw from 3,908 HP to 2,526 HP (2,915 kW to 1,884 kW). This equates to a 47% decrease in SAG unit energy consumption from 8.98 kWh/ton to 4.74 kWh/ton.
- 11% decrease in SAG mill speed (11.5 rpm to 10.3 rpm) indicating optimized ball strikes. Also, the ball chip generation from the SAG mill was reduced considerably.
- 50% increase in pebble discharge rate.
- 7% decrease in ball mill power draw from 4,843 HP to 4,491 HP (3,613 kW to 3,350 kW). This equates to a 24% decrease in ball mill unit energy consumption from 11.13 kWh/ton to 8.43 kWh/ton.
- Ball mill circuit load increased due to the higher throughput with the concurrent decrease in grind size from 78% -200 meshes to 69% - 200 mesh. This is still well within the operating grind target of greater than 62% - 200 mesh.

Assuming a similar ore type over a 30-day month with current electrical costs, operating performance, and mill run-time, the calculated improvements on a monthly basis are:

- 742,320 kWh or $67,000 SAG mill electrical savings.
- 181,786 kWh or $17,100 ball mill electrical savings.
- 77 stph or 4,000 ounces of incremental gold production. This translates to $2.4M incremental revenue increase per month at $600 gold.

7.2 Operating with the TPL™ Design

Aside from the above improvements Cortez Gold Mines realized the following gains:

The SAG mill is significantly steadier mill as opposed to the past cyclical trends. The operators can make small changes in a steady manner without worrying about quick negative circuit responses, whereas big step changes had to be done previous to the TPL™ installation.

The TPL™ resulted in a 3.1 kWh/ton milled reduction in plant operating work index compared to the OEM pulp discharger combined with the new shell liner design (Figure 25).

The plant operating work index has decreased by a nominal 3.6 kWh/ton compared to the OEM shell liner and OEM pulp discharger design (Figure 26).

Steadier SAG ball consumption rates due to the optimized ball strikes and slower mill speed. Cortez is expecting liner life to also increase as a result of the slower mill speeds (Figure 27).
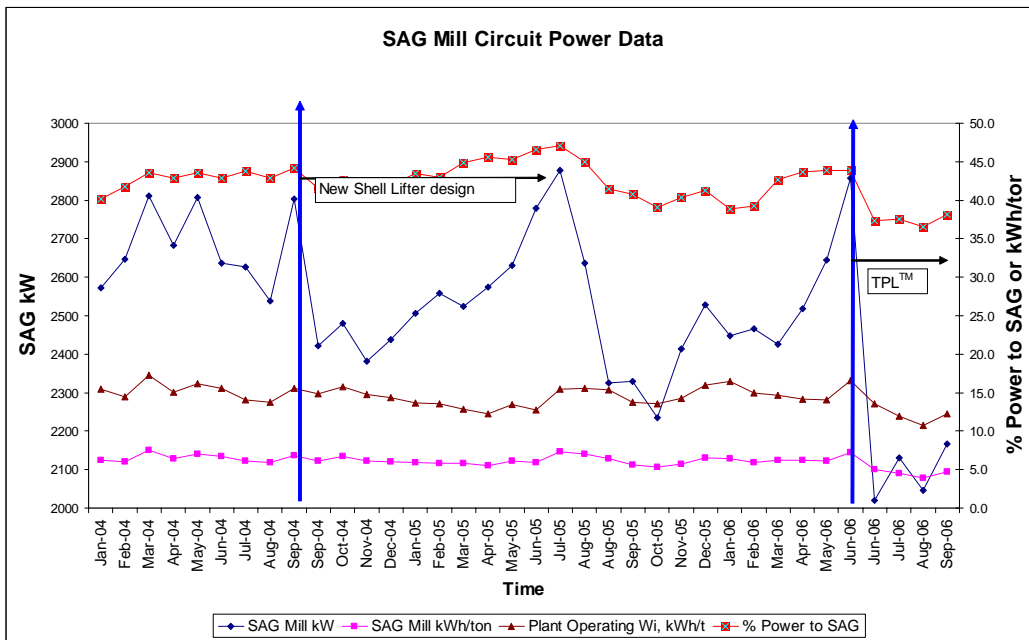
Figure 25: SAG Mill Circuit Power Trend
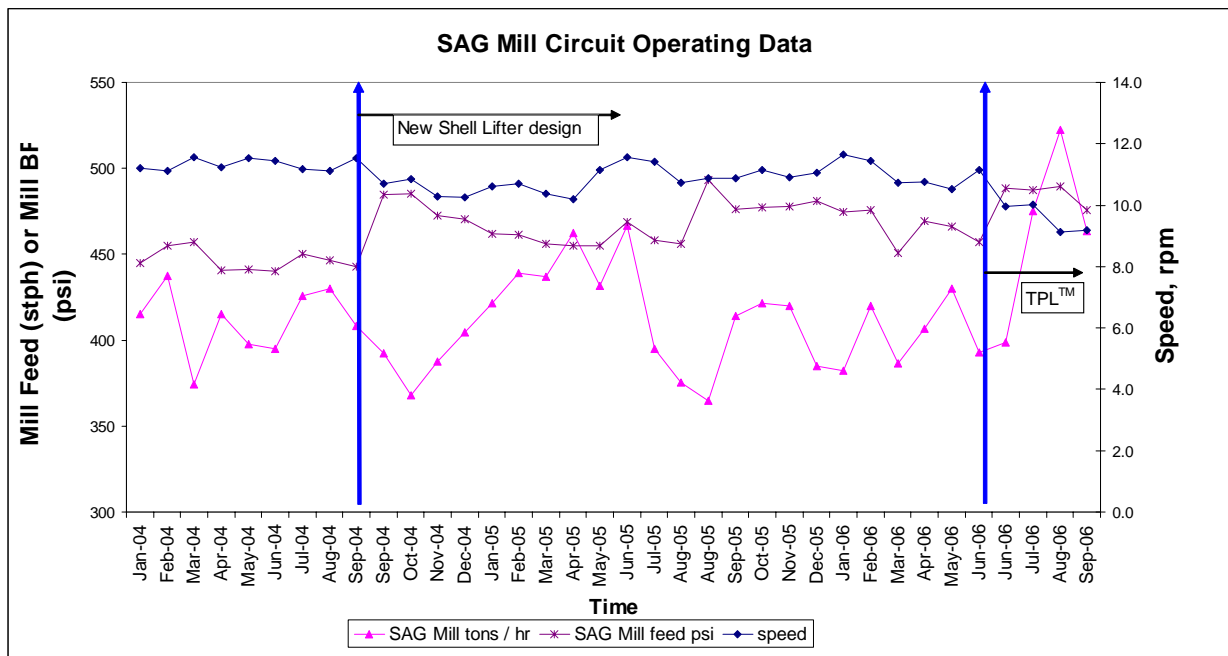
Figure 26: SAG Mill Circuit Operating Trend
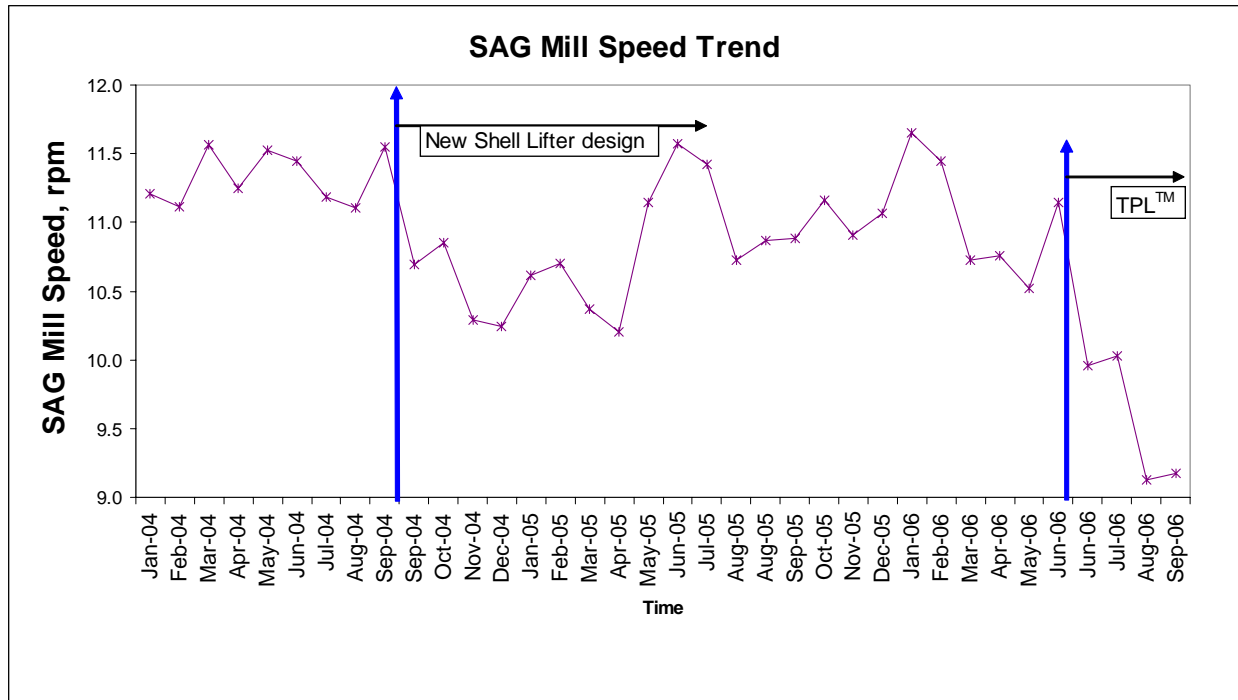
Figure 27: SAG Mill Circuit Speed Trend

8. CONCLUSION

The design of shell lifters and pulp lifters far exceeded expectations. Based on data collected over 90 days after pulp lifter installation, it is projected that Cortez Gold Mines would save 742,320 kWh or $67,000 in SAG mill electrical savings. In the ball milling circuit a saving of 181,786 kWh or $17,100 electrical savings. The increased production of 77 stph translates to 4,000 ounces of incremental gold production. This amounts to $2.4M incremental revenue increase per month at a gold price of $600 per ounce.

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APPENDIX Manuscripts

37TH ANNUAL MEETING OF THE CANADIAN MINERAL PROCESSORS
PROCEEDINGS 2005

Optimizing performance of AG/SAG mills – A design approach

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Key Words

ABSTRACT

Today's high capacity semiautogenous grinding (SAG) mills expend vast amounts of energy and in doing so consume tons of shell liners and steel balls, while processing ore. The energy efficiency of these high-throughput grinding mills can be attributed to the field of breakage and slurry discharge system. The charge motion and breakage of particles inside the mill depends on the shell lifters design, while the discharge of ground particles is controlled by the grate and pulp lifters. The limitations imposed by poor design of grate and pulp lifter become increasingly apparent with increasing size of ag/sag mills and their operation in closed circuit. The design of these mill components has been largely based on trial and error and hence varies considerably between manufacturers. This paper discusses the use of two state of the art design tools - Millsoft™ and FlowMod™. Millsoft™ is an effective tool to design the shell lifters and optimize charge motion, whereas FlowMod™ simulates the slurry discharge system to design grate and pulp lifters. The application of these simulators will be discussed using case studies of full-scale mills.

INTRODUCTION

Many large mining operations around the world have one or more semi-autogenous (SAG) mills doing bulk of the work in their size reduction operation. The SAG mill is usually followed by a ball mill to finish the size reduction prior to the concentration step. In the past when primary, secondary and tertiary crushers fed material directly to large ball mills, the energy efficiency of the concentrator was determined for the most part by the ball mill operation, whereas now the energy efficiency of a plant often rests largely on the SAG mill operation. As a result mines have shifted their emphasis in optimization from ball mills to SAG mills.

There are a number of SAG mills in operation around the world whose diameter reaches up to 40 ft. These operations continually invest in new technologies to improve their energy efficiency and capacity in their SAG circuit. Commercial SAG mill performance is determined by a large number of variables, both mine site variables and mill variables. In many cases these variables dictate production capacity seemingly randomly. Therefore a number of operating philosophies, each specific to a plant, have arisen. In almost all concentrators the SAG operation is a continually evolving operation. Every year, ways and means are sought to increase capacity, decrease energy consumption and prolong lifter and liner life, ore blending, newer designs of lifters, recycle crushing and redesign of grates and trommel screens are a few routes taken at considerable expense.

Operation of SAG Mills

The processing capability of a semi-autogenous (SAG) mill is greatly affected by ore geology and operating variables within the mill. The key issues can be broadly classified in to two categories: field of breakage/ charge motion and flow through the grate and pulp lifters. The field of breakage and charge motion primarily affected by the design of shell lifters and mill speed, which happens inside the mill shell. Once the ore is ground to a size that can pass through the grate holes, the slurry flows into the pulp lifter chamber that transports into the discharge

trunnion. These components of the sag mill are schematically shown in Figure 1 for easier understanding.
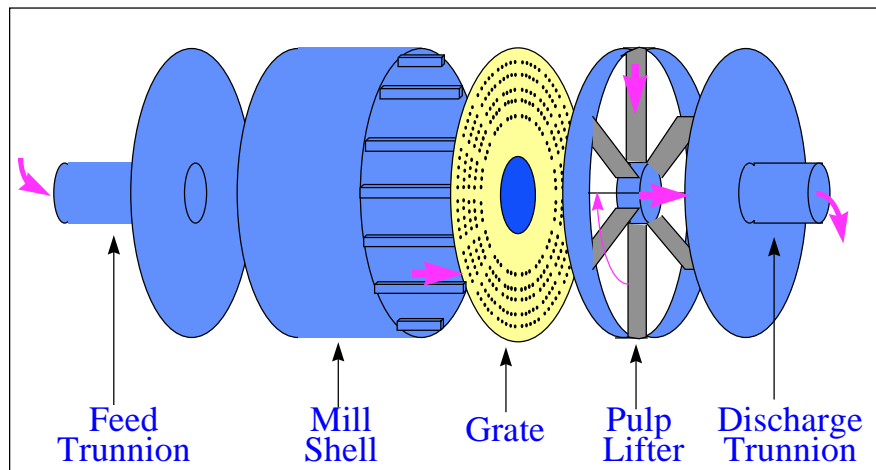
Figure 1 : Schematic of a typical sag mill.

Once slurry has made its way via the grinding media charge its first stage of discharge is via the grates. Hence in the absence of any subsequent restriction the maximum flow capacity that can be obtained for a given mill is determined by the grate design in terms of open area and position of holes. The driving force for slurry transport from the mill shell through the grate holes is the difference in pressure head across the grate.

The major operational problems of sag mills are discussed below

Field of breakage: The motion of charge or rocks and balls in SAG mils can be viewed as a field of breakage generated as a result of the internal profile of the lifters and the rotational speed of the mill shell. The ore entering through the feed port is ground by this field and, if it is sufficiently ground to the grate slot size, the slurry leaves through the slots in the grate. The field of breakage influences the rock mass in the SAG mill. Should the incoming ore be harder and the field of breakage insufficient to reduce the size, the ore stays in the mill longer since it is unable to pass through the grate. The net effect is an increase in rock mass, and the feed rate to the mill must be decreased appropriately to maintain rock to ball ratio. On the other hand, when the ore is soft, the field of breakage reduces the ore size rapidly and hence the rock mass decreases. To sustain a set rock mass, the feed rate must be increased. The complicating factor in this concept of field of breakage is that the incoming rocks themselves constitute the field.

Flow through the grate and pulp lifters: Discharge grates and pulp lifters play an important role in performance of the autogenous (ag), semi-autogenous (sag) mills. The performance of the pulp lifters in conjunction with grate design determines the flow capacity of these mills. The function of the pulp lifters is simply to transport the slurry passed through the discharge grate into the discharge trunnion. Their performance depends on their size and design, the grate design and mill operating conditions such as mill speed and charge level. The difficulties associated with slurry transportation in ag and sag grinding mills have become more apparent in recent years with the increasing trend to build larger diameter mills for grinding high tonnages. This is

particularly noticeable when ag/sag mills are run in closed circuit with classifiers such as fine screens/cyclones.

The performance analysis of conventional pulp lifter designs have shown that a large amount of slurry flows back from pulp lifter into the mill (Latchireddi, 2002, Latchireddi & Morrell, 2003a, 2003b), which depends on the size and design of the pulp lifters. The performance analysis of conventional designs of pulp lifter has shown that a large amount of slurry flows back from pulp lifter into the mill (Latchireddi, 2002). This is because the back face of the pulp lifter is the grate itself, which allows the slurry to flow back into the mill. The field of breakage diminishes when excessive slurry is present in the mill.

Charge motion: In a concentrator, all of the auxiliary equipment-pumps, conveyers, screens and hydrocyclones - and two primary resources-steel and electricity-serve primarily to maintain grinding action in the belly of the SAG mill. It is this action that dictates capacity. This being the case, it is understandable to observe this grinding action continuously from the control room and take whatever steps are necessary to keep the grinding field at its highest potential. Unfortunately, the grinding environment within the mill shell is very severe and none of the on-line instrumentation developed so far has survived the impact of large steel balls striking the shell in operation. Since direct observation is impractical today, the next available option is a simulation of the grinding field to understand the intensity of grinding or lack of intensity of grinding.

Mill power draft: The ore geology, field of breakage and flow through grates and pulp lifters influences each other and the net effect is the build-up of a hold-up level in the mill, which draws a certain power and this power draft is clearly linked with mill throughput. If the interaction can be understood then mill capacity can be understood much more clearly. Then the expectation of increasing capacity at the same level of power draft by one means or another can be safely evaluated.

The electrical energy utilized in a SAG circuit and the consequences are illustrated in Figure 2, wherein five days of operating data in a 32x14 ft SAG mill is illustrated. The power draft of the mill is held between 6 and 7 MW, whereas tons per hour (TPH) of ore feed to the mill shows wide variations between 1000 tph to 1600 tph. When closely examining the circuit performance, one finds that the feed rate drops whenever the power draft shows an increasing trend, whereas intuitive reasoning says that feed rate is proportional to power draft.

The data shows that the specific energy consumed in processing, i.e kWh/tonne of ore is not steady, as one would expect for a typical ore body. Even within a 24 hour time frame, where the feed ore hardness may be assumed constant, the variation in feed rate is drastic. The internal dynamics within the SAG mill, as exemplified by the three broad concepts, are causing wide fluctuations in grinding rate, which in turn is reflected as capacity.

Figure 2: Five days of plant operating data:32x14 ft SAG circuit.
(TPH-fresh feed rate, MW-mill power in megawatts)

SAG Mill Efficiency

The efficiency of SAG mills depends on the breakage rate of particle sizes present in the mill. The breakage rate in turn depends on the power draft of the mill for the simple reason *work done (in fracturing ore particles) is directly proportional to energy input*. The power delivered to the mill should be efficiently transferred to the bed of ore particles in the mill to achieve maximum efficiency. There are four principal operational factors that influence this power delivery. They are: *Mill filling, Mill rotational speed, Design of Shell lifters, and Slurry transport through the grate and pulp lifters.*

There are mainly two kinds of models that have been proposed and currently in use in the industry: *Semi-empirical, and Discrete* element method (Rajamani et.al., 1996,1997a,1997b and Mishra and Rajamani 1994a 1994b,). The empirical models predict the power essentially based on the principle torque-arm, i.e, the torque required to sustain the load dynamically. However, these models do not incorporate the influence of the other two important factors- *shell lifter design and slurry transport through grate and pulp lifters*.

The energy efficiency of tumbling mills can be directly examined by looking at the motion of rocks and steel balls inside the mill. The make-up of the charge and the lifter bars attached to the inside of the mill shell can be designed particularly to maximize the mass of ore fractured per unit of energy spent. At the same time, the unnecessary collisions of steel balls against the mill shell can be reduced. Furthermore, the cascading charge flow can be altered in such a way as to maximize grinding efficiency. First, the shell lifters are designed in such a way the motion is fully cascading and that part of cateracting motion is made to strike in the vicinity of the toe. In such a charge motion regime both shearing action and impacts are fully utilized in grinding the ore.

The key issues discussed above largely depend on the two important design factors such as the shell lifters and grate-pulp lifters. Both these design factors undergo periodic changes, usually

once or twice a year, toward more optimal design. The design of these two important mill components has been largely based on trial and error and hence varies considerably between manufacturers.

The research work carried out by Rajamani and Latchireddi over the years has led to the development of two important tools – Millsoft™ and FlowMod™, to help the designers and engineers to analyze and understand the influence of the internal components of sag mills – shell lifters, grate and pulp lifters respectively. The following sections will discuss the basic principles and application of these two simulators with case studies.

Millsoft™ - Discrete Element Simulation of SAG Mills

The SAG mill is made up of cylindrical shell with two conical shells attached on both ends. Lifter elements are attached in both the cylindrical and conical shell sections. As the SAG mill rotates, typically around 10 rpm, the internal flat walls of the lifter and shell imparts momentum to balls and rocks. The momentum is primarily transferred to particles in direct contact with the plate elements. These particles in turn impart their momentum to adjacent layers of particles. In this manner the motion of the entire charge evolves resulting in what is commonly referred to as cascading and cataracting charge.

The discrete element method embedded in MillSoft™ replicates the evolution of charge motion as described above. In the simulation the exact dimensions of lifters, plates and balls are used. First, the mill shell is constructed with a series of flat planes joining together to form cylindrical shell and conical shell. Next, a series of planes are constructed on the shell to duplicate shell lifters and end lifters. Next, the grinding balls and rock particles are generated. Usually the rock particles are constructed as spherical particles for ease of computations. The number of spheres so constructed would correspond to 25% filling with 12% filling for grinding balls. In three dimentional simulation, the number of spheres may be in the range 200,000 to 1,000,000 depending on the size distribution and size of the SAG mill. In two dimension, the number of spheres is in the 3000-8000 range. Now, in the numerical computational point of view, a complex polygonal assembly of rectangular plates enclose a large number of spheres. These spheres have different collisional properties which depend on their size and material make-up.

The critical aspect of DEM is the modeling of the collision between any two spheres or the sphere and a plate element. At the contact point a force develops which sends the sphere in a direction away from the point of collision and also there is deformation of the metal or fracture of the rock particle. To account for these two events the collision is modeled by a pair of spring and dashpot. The spring models the opposing force and the dashpot models the dissipation of the force. Force is dissipated as a result of deformation of the material at the point of collision. The spring and dashpots in the model are placed in the normal direction as well as the tangential plane of the collision point. Thus after collision forces are calculated, the acceleration and velocity of the pair of spheres are computed with the familiar laws of physics. It is clear then that in this method the forces of collision and the dissipation of energy are calculated at a greater level of detail than any other available models.

MillSoft can be used affectively to show the effects of different lifter configurations, mill loading, mill speed, and other operating conditions. Unlike single-particle trajectory programs which show only the worse-case condition of a particle path, MillSoft takes into account the entire charge, you can effectively see the "kidney" shape of the charge, the dead zone, toe and shoulder of the charge, and areas of high-impact on the mill lifters.

Millsoft can also be used to follow lifter wear, shell plate wear and particle breakage. Most importantly, the location and the intensity of impacts on lifter bars can be computationally recorded and a corresponding metal abrasion at that location can be worked out. In a like manner, the energy of impact can be used to fragment the rock particles in the simulation. However, the distribution and number of fragments produced overwhelms the computational task.

Shell lifter design and charge motion analysis with Millsoft™

A typical example of charge motion analysis with Millsoft™ is illustrated in this section. The SAG mill under consideration is a 38x24 ft mill drilled for 60 shell lifters. Therefore, the mill can be fitted with 30 high and 30 low lifter sets or a total of 60 high lifters. The total charge is 27% with 15% balls. The mill is expected to draw 15-18 MW power. The mill speed is set at 76% critical speed. The snapshots of the charge motion at different conditions are shown in Figure 3.

(a) Top hat (7°)   (b) 25° release angle   (c) 35° release angle

Figure 3: Snap shots of charge motion.

Figure 3a shows the SAG mill fitted with traditional lifters. The high lifters are the top hat type with a 7 degree release angle. The velocity vectors are super imposed on the balls and rock particles. A close look reveals within the cascade the central region where grinding action is minimum. Due to small release angle, considerable amount of rock and ball particles are thrown against the mill shell. The ball-to-liner strike zone extends as high as 9 O'clock mark. The mill may not reach design capacity, especially with hard ore type. Furthermore, considerable damage to liners is imminent within four months of operation.

Next, we consider the same mill fitted with 30 high lifters and 30 low lifters of 25-degree release angle. Figure 3b shows the snap shot of charge animation. Here, ball strikes on liners are seen nearly up to 8 O'clock position, a considerable improvement over Figure 3a. This lifter is suitable for maintaining a moderately aggressive charge motion at the expense of shorter lifter wear life.

Next, the release angle increased to 35 degree with 30 high lifters whose animation is shown in Figure 3c. The cataracting charge lands within the toe of the charge. This type of charge motion is ideal for SAG, for it to preserve the lifters. The mill speed may be increased without fear of damaging liners. Alumbrera mines exploited this concept to increase production. With such lifters, Alumbrera even used 150 mm top ball size.

Industrial case studies on shell lifters
In recent years, with increasing mill size whose power draw has reached over 20MW, emphasis has been diverted towards the design of shell lifters to increase the grinding efficiency. Lifters are not only consumables for protection against wear, but also critical machine elements. They transfer power to the mill charge and govern the pattern of energy distribution inside the mill, including affecting the grinding kinetics. The performance of liners changes with time, as their shape changes by wear. A good design must take these restrictions into consideration and optimize the performance of liners for the full duration of their useful life. The attainment of expected useful life of a set of lifters depend not only on their initial shape, material and quality of fabrication but a good matching between expected and real operating conditions inside the mill. The main issue is the direct impact of balls on the lifters in the absence of the damping effect of a bed of mineral ore and ball charge. In the following, the capacity increase achieved with newer shell lifter designs using Millsoft or other methods is discussed.

Collahuasi Mines, Chile is a 65,000-tpd operation. It employs two 32 X 15 ft variable speed SAG mills and four 22 x 36 ft ball mills. The original lifters had a face angle of 6 degrees and therefore the SAG mills suffered a throughput restriction. According to Marcelo Villouta (2001), plant manager, "the original SAG mill liner design, Hi-Hi with a 6 deg contact angle, was changed to a 17 deg face angle and then with Dr. Rajamani's (Millsoft code) assistance a new design, Hi-Hi with 30 deg contact angle was installed in SAG mills. A noticeable 11% increase in ore throughput was achieved.

Alumbrera Mines, Argentina (Sherman, 2001) is a copper ore operation treating between 70,000 to 100,000 tpd of ore depending on the rock type presented to mill feed. Two SAG mills of 30X15 ft are used in this circuit. The original design called for 72 rows of 9° lifters. These lifters resulted in drop in the capacity to 50,000 tpd. Within 6 months of start of operations a new lifter design was explored with Millsoft simulations. As a result, the lifter set was changed to 48 rows of 25° lifters and later to 36 rows of 30° lifters. These lifters increased the throughput steadily to 96,000 tpd. Even today, lifter design is constantly modified along with the use of larger size (6 " as opposed to 5.5 ") to increase production while processing hard ores.

Candelaria Mines, Chile is a 65,000 tpd operation. The grinding circuit includes two 36x15 ft SAG mills. The original lifters were 72 rows of rail design with 10-degree release angle. A year

later the release angle was changed to 20 degrees. Another year later, the shell lifter design adopted was a 36 rows of 35 degree release angle. This design eliminated packing between lifters, throughput increased by 15%, the wear was slightly better than traditional lifters and the power draw in the first month was much higher compared to previous designs.

Los Pelambres Mines, Chile is a 120,000-tpd operation. The SAG mill size is 36x17 ft. the first shell lifter design was 72 rows of 8 degrees release angle. However, severe packing was noticed which was the reason for lower capacity. Subsequently, Millsoft simulation software was used to explore better design. The new lifter design was 36 rows of 30-degree release angle. This design increased throughput by 10,000 tpd.

FlowMod™ – A Tool for Grate and Pulp Lifter Design
Recently, much attention has been focused on the grate/pulp lifter assembly, as the objective has been shifted to maintain very high throughput in closed circuit SAG mill operations. This has emphasized the operational problems in removing high volumes of slurry and pebbles via the grates and pulp lifters.

Pulp lifters (also known as pan lifters) are an important component of these mills whose function is to transport the slurry flowing through the grate holes into the discharge trunnion and out of the mill as shown in Figure 4. Although pulp lifters are obviously important in determining the ultimate discharge flow capacity, very little work has been reported either on their performance or on their influence on mill efficiency.
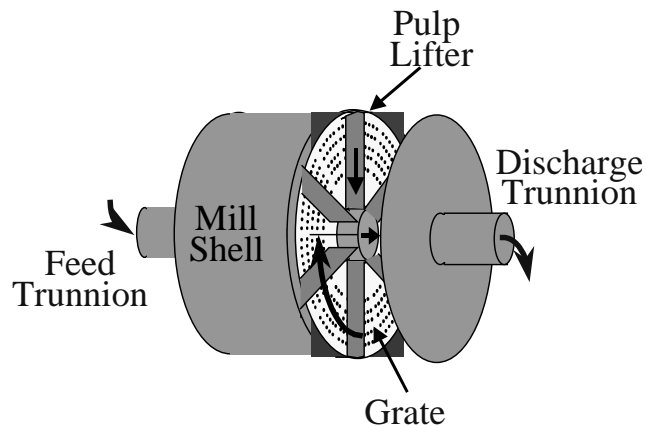
Figure 4: Typical arrangement of Grate and Pulp lifters in SAG mills

The design of grate/pulp lifters in SAG mills has a substantial impact on the behavior of the mill. If sufficient grate open area and pulp lifter capacity is not available, they will provide a high resistance to flow of slurry resulting in excessive amount of slurry resulting in slurry pool formation inside the mill. If the amount of slurry exceeds a level past where efficient grinding occurs, the mill will "go off the grind" (Moys, 1986 and Austin et.al, 1984). Build-up of large volumes of slurry will have serious problems by reducing the effective density of the submerged media to a low level, which reduces the inter-media forces that are responsible for grinding of finer particles. The presence of slurry pool tends to reduce the power draw and grinding performance.

The design of both grate and pulp lifters have been largely based on trial and error and hence vary considerably between manufacturers. FlowMod™ is a steady state simulation software has been developed to estimate the slurry hold-up inside the mill and its profile with respect to the charge profile at any given operating condition (Figure 5b). It takes all the important mill design and operating parameters (Figure 5a) into consideration while computing the slurry hold-up-discharge rate relation. It allows the user to study the effects of different grate designs (open area and position of slots), pulp lifter design (size and shape), mill loading, mill speed, solids concentration and other operating conditions. It also shows the slurry pooling and its effect on mill power draw.
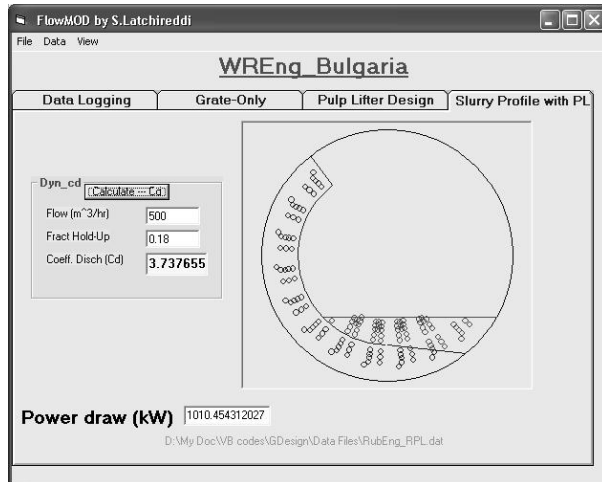
Figure 5: FlowMod's a) user interface and b) slurry hold-up and its profile.

Performance of pulp lifters

A detailed investigation by Latchireddi (2002), Latchireddi and Morrell (1997, 2003a and 2003b) on impact of the discharge grate and pulp lifters on slurry transport in SAG mills revealed the limitations of the conventional designs of pulp lifters (Radial and Curved) on slurry transport in SAG mills. The performance of pulp lifters in transportation of slurry passed through the discharge grate are illustrated in Figure 5. For an efficient slurry transport though the mill, the discharge capacity of pulp lifters should match with the discharge capacity of grate-only at any given slurry hold-up.
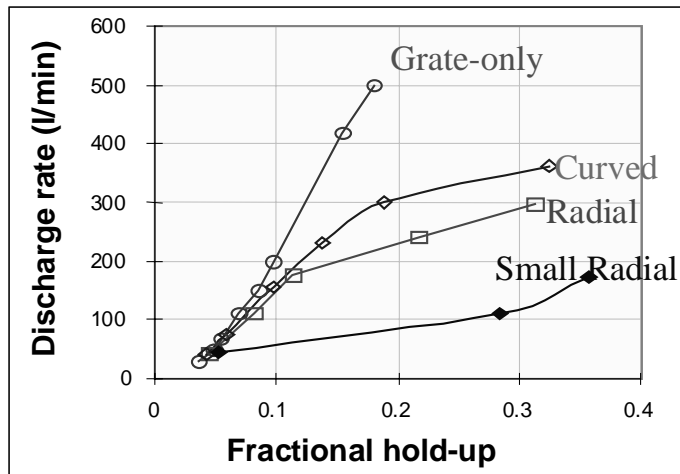
Figure 5: Flow of slurry through grate and pulp lifters.

The reason for the significantly inferior performance of the conventional pulp lifters is the Flow-back phenomena. The flow-back of slurry from pulp lifters into the main grinding chamber through the grate can be as high as 60% depending on the design and size of the pulp lifter assembly. The fraction of slurry remained in the pulp lifter gets carried over to the next cycle as carry-over fraction, however, this occurs in mills operating at higher speeds. The overall slurry transportation process in AG/SAG mills is summarized in Figure 6.
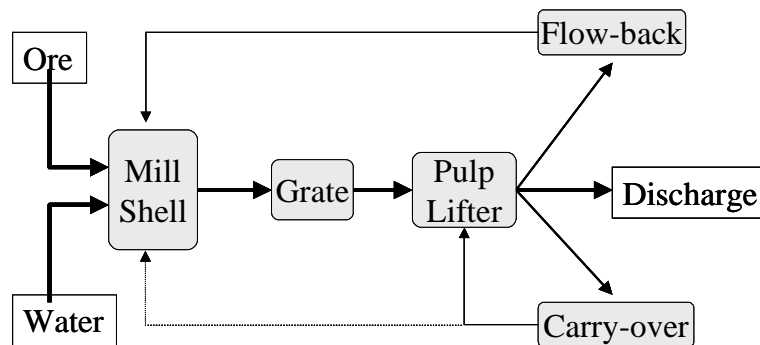
Figure 6: Process of slurry transportation in SAG mill

The excess slurry due to flow-back process accumulates near the toe region resulting in slurry pool formation (Figure 7). This slurry pool softens the ball strikes at the toe of the charge which inhibits the impact breakage of particles. It also diminishes the shearing action in the cascading charge which reduces the fine particle grinding. Both these aspects adversely affect the grinding efficiency thus reduce the mill capacity. Furthermore, the slurry pool applies a counter torque in the mill effectively reducing the power draft. Therefore, the operator either increases the feed rate or increases the critical speed to increases power draft, the power draft increases at first but decreases later, thus giving a false indication.
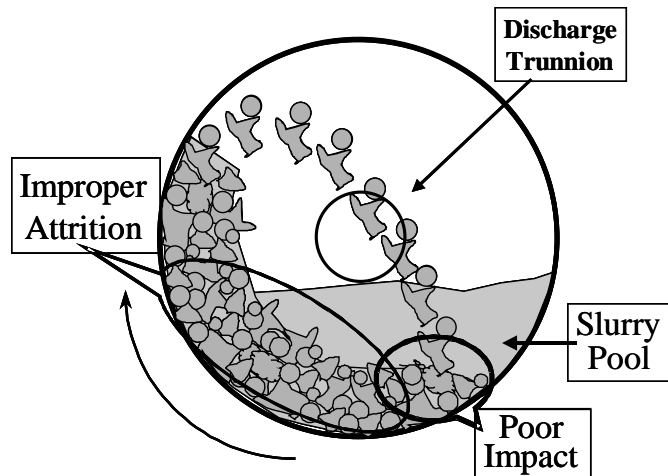
Figure 7: Adverse effect of slurry pooling on grinding process in SAG mill

Development of new pulp lifter design

The only way to overcome the restrictions imposed by the conventional designs which restricts the flow capacity of mills is to ensure no flow-back of slurry occurs once the slurry has entered the pulp lifter. This has been achieved by developing a new design of pulp lifter called the Twin Chamber Pulp Lifter -TCPL (Latchireddi 1996 and Latchireddi & Morrell 1997b) a schematic of which is shown in Figure 8.
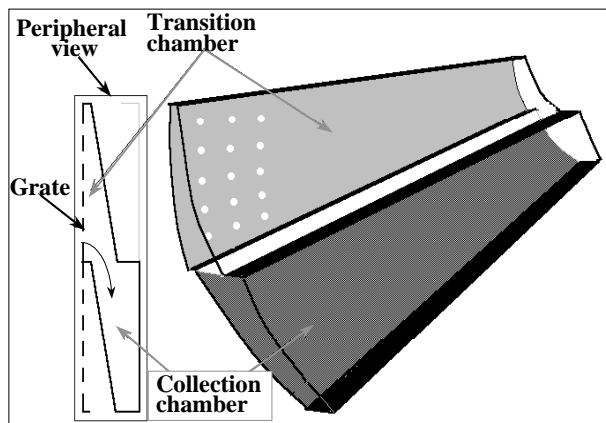
Figure 8: Schematic of the Twin Chamber Pulp Lifter (TCPL).

The slurry will enter the section exposed to the grate - called the transition chamber, and then flow into the lower section - called the collection chamber which is not exposed to the grate. This mechanism ensures that the slurry is unable to flow or drain backwards into the mill, and hence the flow-back process is prevented up to the capacity of the collection chamber.

The TCPL can be precisely designed to handle the designed flow capacity of the mill whose dimensions depends on the operating conditions such as mill speed and number of pulp lifter segments.

Influence of grate open area and charge volume on performance of TCPL

Besides overcoming the major problem of flow-back, which is unavoidable in case of conventional pulp lifter designs, the unique design of TCPL offers many other advantages. The most important one is that its performance does not get affected due to variations in:
grate open area, and
volume of grinding media (charge) inside the mill

In ag/sag mills the volume of the grinding media (balls & coarse ore) tends to change with the type of ore which also has strong interaction with grate open area and influences the performance of pulp lifter. To illustrate these points the variation in mill hold-up-discharge rate relation with change in grate open area and charge volumes are shown in Figure 9 and Figure 10 respectively for RPL and TCPL.
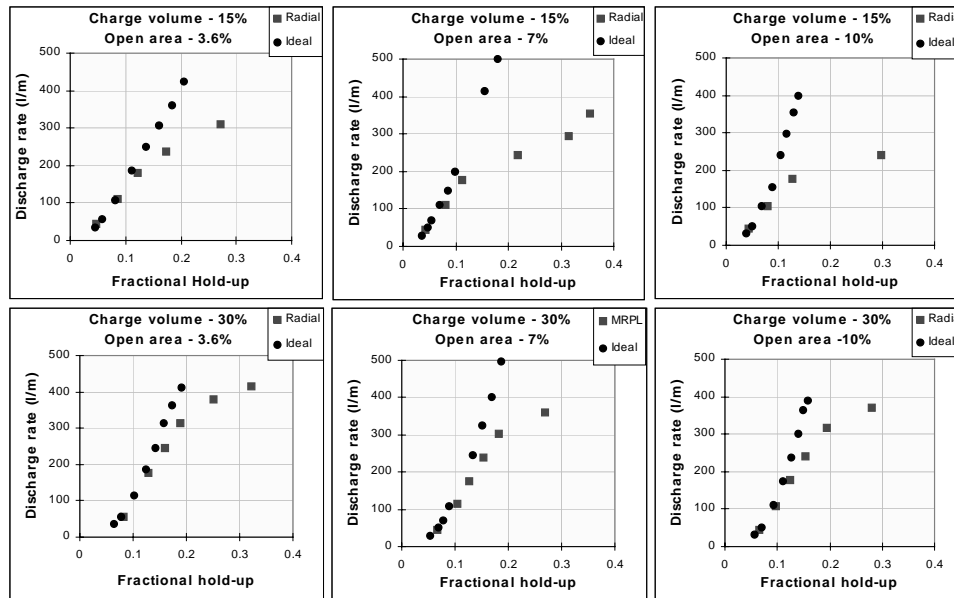
Figure 9: Performance of RPL with variations in charge volume and open area.

The observation of decreasing discharge rates with increasing grate open area is in accordance to the statement made by Rowland and Kjos (1975), that if the pulp lifters do not have enough capacity, the typical approach of increasing the grate area does not improve the situation but makes it worse by allowing the slurry to flow back into the mill, causing it to run too wet. Morrell and Kojovic, (1996) have mentioned that the presence of excessive slurry pool inside the mill reduces the grinding efficiency.
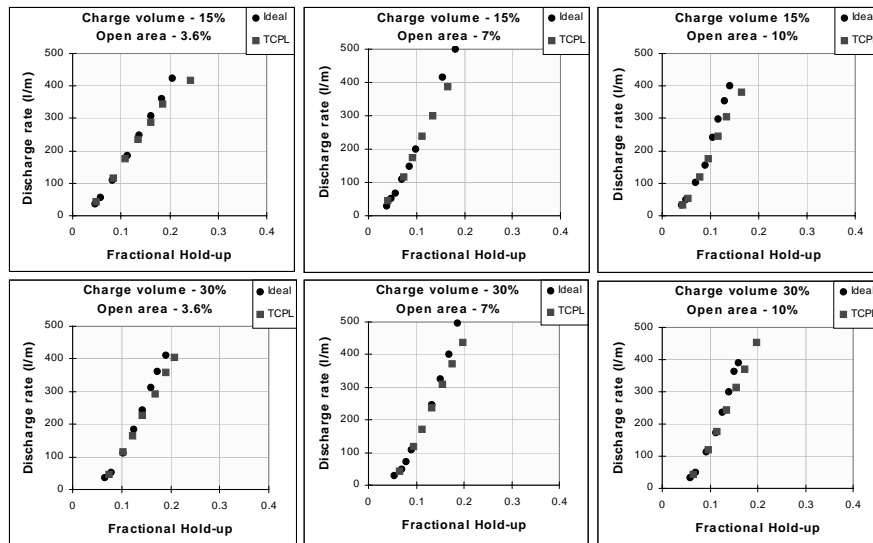
Figure 10: Performance of TCPL with variations in charge volume and open area.

Contrary to the observations made from the RPL results shown in Figure 9, it may be seen from Figure 9 that the performance of the TCPL is not adversely affected by changes in grate open area and charge volume. This observation is clearly seen up to the discharge capacity of the collection chamber. This is because once the slurry flows into the collection chamber it is not exposed to the grate holes. However, the influence of the charge volume and open area, which is similar to that in the RPL, can be seen at discharge rates exceeding the capacity of the collection chamber.

Comparing Figure 9 with that of Figure 10, it is quite evident that up to the capacity of the collection chamber, the performance of TCPL is not adversely influenced by changes in grate open area and charge volume inside the mill.

Industrial trials of twin chamber pulp lifter

The clear ability of the TCPL to achieve a higher discharge flow rate, closer to the maximum flow capacity of the mill, for a given hold-up prompted Alcoa World Alumina Australia to trial this design in one of its 7.7 m diameter sag mills at its Wagerup Refinery in Western Australia in August 1999.

To assess the effect of the TCPL over the existing RPL, a complete survey around the sag mill circuit was conducted both before and after the installation. For the survey prior to installation the mill was running at its maximum capacity, at which point slurry just starts to overflow out of the feed end of the mill. This was followed by running the mill at different throughputs to estimate the maximum capacity that could be achieved under the prevailing operating conditions. All the surveys were followed by a crash stop of the mill to measure the instantaneous charge and slurry volumes. The slurry hold-up values at different feed tonnage going through the mill for both pre and post installation of the TCPL are shown in Figure 11. The ideal slurry hold-ups required to fill the voids of media without any slurry pooling are also shown for comparison.
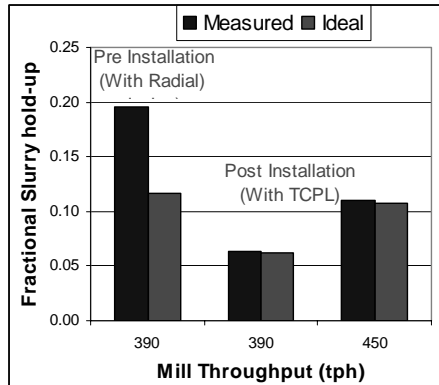
Figure 11: Slurry hold-up and mill throughput relation

It can be seen that at the pre-TCPL installation the maximum throughput was 390 tph and the slurry hold-up was almost 20% by volume. When the mill was crash stopped a slurry pool of more than 0.7 meters deep was measured above the charge level. After installation of the TCPL the hold-up reduced to 6% and the slurry pool disappeared. This resulted in a higher throughput being achieved, which increased, from 390 to 450 tph. Despite the 15% increase in mill throughput, the product size distribution has remained unaffected (Denis et al, 2001.

CONCLUSIONS

It is shown that the design of both shell lifters and grate-pulp lifter assembly are crucial for optimal performance of the ag/sag mills. The design of shell lifters, which control the charge motion thus the breakage field, can be optimized using Millsoft™ - a discrete element numerical method. It can be used affectively to show the effects of different lifter configurations, mill loading, mill speed, and other operating conditions. It can also be used to follow lifter wear, shell plate wear and particle breakage. FlowMod™ is a steady state simulator to optimize the design of grate and pulp lifters to handle the given flow through the mill. It estimates the slurry hold-up inside the mill and shows its dynamic surface at any mill operating condition. The program allows changes in grate open area, position of holes, size of pulp lifter and its shape besides the operating parameters.

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SIMULATION OF BALL AND ROCK CHARGE MOTION
IN SEMIAUTOGENOUS MILLS FOR THE DESIGN OF SHELL AND PULP LIFTERS

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ABSTRACT

Today's high capacity semiautogenous grinding (SAG) mills expend vast amounts of energy and in doing so consume tons of steel balls and shell liners, while processing ore. The energy efficiency of these mills can be directly examined by looking at the motion of rocks and steel balls inside the mill. The make-up of the charge and the lifter bars attached to the inside of the mill shell can be designed particularly to maximize the mass of ore fractured per unit of energy spent. At the same time, the unnecessary collisions of steel balls against the mill shell can be reduced. Furthermore, the cascading charge flow can be altered in such away as to maximize grinding efficiency. The harsh environment of the mill interior prevents any instrumentation from being placed. The simulation of charge motion in tumbling mill became practical with the emergence of the discrete element method (DEM).

In the last decade, the DEM for simulation of tumbling mills has advanced sufficiently that it has become a very practical tool in the mining industry. This presentation gives an overview of the DEM as applied to the tumbling mill problem. Both the two- and three-dimensional (2-d and 3-d, respectively) models as well as the parallelization of the 3-d code are described. Also, the discrete element method can be readily applied to the simulation of the motion of broken rock particles and pebbles in pulp lifters. Pulp lifters play a critical role and in conjunction with grates, they control the mill capacity. This technology will alone bring about a major improvement in energy efficiency in SAG mills.

INTRODUCTION

Many large mining operations around the world have one or more semi-autogenous (SAG) mills doing bulk of the work in their size reduction operation. The SAG mill is usually followed by a ball mill to finish the size reduction prior to the concentration step. In the past when primary, secondary and tertiary crushers fed material directly to large ball mills, the energy efficiency of the concentrator was determined for the most part by the ball mill operation, whereas now the energy efficiency of a plant often rests largely on the SAG mill operation. As a result mines have shifted their emphasis in optimization from bal mills to SAG mills.

There are a number of SAG mills in operation around the world whose diameter reaches up to 40 ft. These operations continually invest in new technologies to improve their energy efficiency and capacity in their SAG circuit. In a later section, optimization of shell lifters will be described.

Commercial SAG mill performance is determined by a large number of variables, both mine site variables and mill variables. In many cases these variables dictate production capacity seemingly randomly. Therefore a number of operating philosophies, each specific to a plant, have arisen. In almost all concentrators the SAG operation is a continually evolving operation. Every year, ways and means are sought to increase capacity, decrease energy consumption and prolong lifter and liner life, ore blending, newer designs of lifters, recycle crushing and redesign of grates and trommel screens are a few routes taken at considerable expense.

SAG Mill Operational Problems

The processing capability of a semi-autogenous (SAG) mill is greatly affected by ore geology and operating variables within the mill. The key issues are broadly classified in to three categories: field of breakage, flow through the grate and pulp lifters and charge motion.

Field of breakage: The motion of charge or rocks and balls in SAG mils can be viewed as a field of breakage generated as a result of the internal profile of the lifters and the rotational speed of the mill shell. The ore entering through the feed port is ground by this field and, if it is sufficiently ground, the slurry leaves through the slots in the grate. The field of breakage influences the hold-up mass in the SAG mill. Should the incoming ore be harder and the field of breakage insufficient to reduce the size, the ore stays in the mill longer since it is unable to pass through the grate. The net effect is an increase in hold-up mass, and the feed rate to the mill must be decreased appropriately to maintain hold-up. On the other hand, when the ore is soft, the field of breakage reduces the ore size rapidly and hence the hold-up mass decreases. To sustain a set hold-up the feed rate must be increased. The complicating factor in this concept of field of breakage is that the incoming rocks themselves constitute the field.

Flow through the grate and pulp lifters: The discharge of fine material through the numerous slots in the grate is poorly understood not because of any lack of physical methodology but due to the unpredictable events occurring in the vicinity of the grate. Balls and pebbles constantly cover up numerous slot openings and the slurry finds its way around the balls and pebbles. Furthermore, small pebbles permanently lodge themselves in these slots and at random times they dislodge. To release the larger sized pebbles, usually pebble ports, although fewer in number, are provided one the grate. The net effect of all these phenomena is that the slurry flow through a grate can not be predicted reliably. The slurry, after passing through the grate enters the pulp lifter and flows into trammel. However, since the back face of the pulp lifter is the grate itself, part of the slurry flows into the mill itself. The field of breakage diminishes when excessive slurry is present in the mill.

Charge motion: In a concentrator, all of the auxiliary equipment-pumps, conveyers, screens and hydrocyclones - and two primary resources-steel and electricity-serve primarily to maintain grinding action in the belly of the SAG mill. It is this action that dictates capacity. This being the case, it is understandable to observe this grinding action continuously from the control room and take whatever steps are necessary to keep the grinding field at its highest potential. Unfortunately, the grinding environment within the mill shell is very severe and none of the on-line instrumentation developed so far has survived the impact of large steel balls striking the shell in operation. Since direct observation is impractical today, the next available option is a simulation of the grinding field to understand the intensity of grinding or lack of intensity of grinding.

Mill power draft: The ore geology, field of breakage and flow through grates and pulp lifters influences each other and the net effect is the build-up of a hold-up level in the mill, which draws a certain power and this power draft is clearly linked with mill throughput. If the interaction can be understood then mill capacity can be understood much more clearly. Then the expectation of

increasing capacity at the same level of power draft by one means or another can be safely evaluated.

The electrical energy utilized in a SAG circuit and the consequences are illustrated in Figure 1, wherein five days of operating data in a 32x14 ft SAG mill is illustrated. The power draft of the mill is held between 6 and 7 MW, whereas tons per hour (TPH) of ore feed to the mill shows wide variations between 1000 tph to 1600 tph. When closely examining the circuit performance, one finds that the feed rate drops whenever the power draft shows an increasing trend, whereas intuitive reasoning says that feed rate is proportional to power draft.
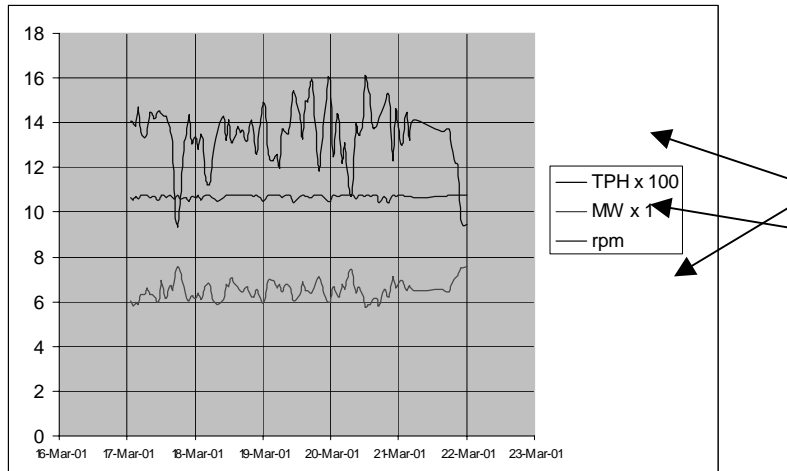
Figure 1: Five days of plant operating data:32x14 ft SAG circuit.
(TPH-fresh feed rate, MW-mill power in megawatts)

The data shows that the specific energy consumed in processing, i.e kWh/tonne of ore is not steady, as one would expect for a typical ore body. Even within a 24 hour time frame, where the feed ore hardness may be assumed constant, the variation in feed rate is drastic. The internal dynamics within the SAG mill, as exemplified by the three broad concepts, are causing wide fluctuations in grinding rate which in turn is reflected as capacity.

SAG Mill Efficiency

The efficiency of SAG mills depends on the breakage rate of particle sizes present in the mill. The breakage rate in turn depends on the power draft of the mill for the simple reason *work done (in fracturing ore particles) is directly proportional to energy input*. The power delivered to the mill should be efficiently transferred to the bed of ore particles in the mill to achieve maximum efficiency. There are four principal operational factors that influence this power delivery. They are: *Mill filling, Mill rotational speed, Design of Shell lifters, and Slurry transport through the grate and pulp lifters.*

There are mainly two kinds of models that have been proposed and currently in use in the industry: *Semi-empirical, and Discrete* element method (Rajamani et.al., 1996,1997a,1997b and Mishra and Rajamani 1994a 1994b,). The empirical models predict the power essentially based

on the principle torque-arm, i.e, the torque required to sustain the load dynamically. However, these models do not incorporate the influence of the other two important factors- *shell lifter design and slurry transport through grate and pulp lifters*.

The energy efficiency of tumbling mills can be directly examined by looking at the motion of rocks and steel balls inside the mill. The make-up of the charge and the lifter bars attached to the inside of the mill shell can be designed particularly to maximize the mass of ore fractured per unit of energy spent. At the same time, the unnecessary collisions of steel balls against the mill shell can be reduced. Furthermore, the cascading charge flow can be altered in such a way as to maximize grinding efficiency. First, the shell lifters are designed in such a way the motion is fully cascading and that part of cateracting motion is made to strike in the vicinity of the toe. In such a charge motion regime both shearing action and impacts are fully utilized in grinding the ore.

The key issues discussed above largely depend on the two important design factors such as the shell lifters and grate-pulp lifters. Both these design factors undergo periodic changes, usually once or twice a year, toward more optimal design. The discrete element method treats every individual grinding ball and rock as separate entities and calculates the forces of collision and the subsequent evolution of the particle motion and breakage.

Discrete Element Simulation of SAG Mills

The SAG mill is made up of cylindrical shell with two conical shells attached on both ends. Lifter elements are attached in both the cylindrical and conical shell sections. As the SAG mill rotates, typically around 10 rpm, the internal flat walls of the lifter and shell imparts momentum to balls and rocks. The momentum is primarily transferred to particles in direct contact with the plate elements. These particles in turn impart their momentum to adjacent layers of particles. In this manner the motion of the entire charge evolves resulting in what is commonly referred to as cascading and cataracting charge.

The discrete element method embedded in MillSoft replicates the evolution of charge motion as described above. In the simulation the exact dimensions of lifters, plates and balls are used. First, the mill shell is constructed with a series of flat planes joining together to form cylindrical shell and conical shell. Next, a series of planes are constructed on the shell to duplicate shell lifters and end lifters. Next, the grinding balls and rock particles are generated. Usually the rock particles are constructed as spherical particles for ease of computations. The number of spheres so constructed would correspond to 25% filling with 12% filling for grinding balls. In three-dimentional simulation, the number of spheres may be in the range 200,000 to 1,000,000 depending on the size distribution and size of the SAG mill. In two dimensions, the number of spheres is in the I the range of 3000-8000. Now, in the numerical computational point of view, a complex polygonal assembly of rectangular plates encloses a large number of spheres. These spheres have different collisional properties, which depend on their size and material make-up.
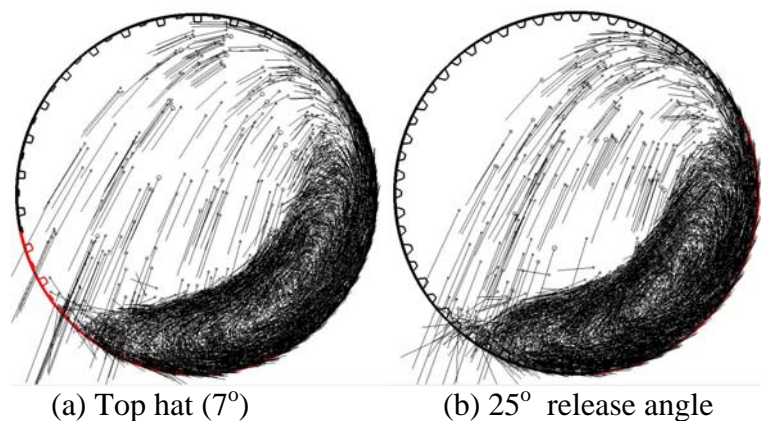
The critical aspect of DEM is the modeling of the collision between any two spheres or the sphere and a plate element. At the contact point a force develops which sends the sphere in a

direction away from the point of collision and also there is deformation of the metal or fracture of the rock particle. To account for these two events the collision is modeled by a pair of spring and dashpot. The spring models the opposing force and the dashpot models the dissipation of the force. Force is dissipated as a result of deformation of the material at the point of collision. The spring and dashpots in the model are placed in the normal direction as well as the tangential plane of the collision point. Thus after collision forces are calculated the acceleration and velocity of the pair of spheres are computed with the familiar laws of physics. It is clear then that in this method the forces of collision and the dissipation of energy are calculated at a greater level of detail than any other available models.

Hence, one can use forces and dissipated energy to follow lifter wear, shell plate wear and particle breakage. Most importantly, the location and the intensity of impacts on lifter bars can be computationally recorded and a corresponding metal abrasion at that location can be worked out. In a like manner, the energy of impact can be used to fragment the rock particles in the simulation. However, the distribution and number of fragments produced overwhelms the computational task.

Shell lifter Design and Charge Motion Analysis with Millsoft

A typical example of charge motion analysis with Millsoft is illustrated in this section. The SAG mill under consideration is a 38x24 ft mill drilledfro 60 shell lifters. Therefore, the mill can be fitted with 30 high and 30 low lifter sets or a total of 60 high lifters. The total charge is 27% with 15% balls. The mill is expected to draw 15-18 MW power. The mill speed is set at 76% critical speed. The snapshots of the charge motion at different conditions are shown in Figure 2.

(a) Top hat (7°)   (b) 25° release angle

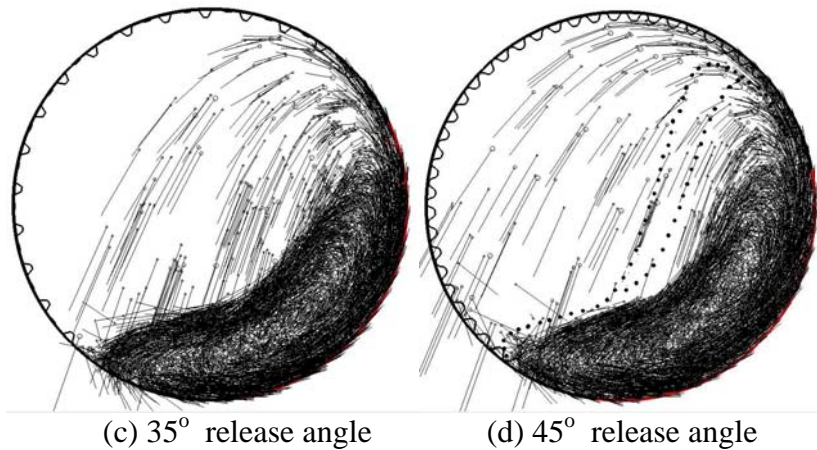(c) 35° release angle   (d) 45° release angle

Figure 2: Snap shots of charge motion.

Figure 2a shows the SAG mill fitted with traditional lifters. The high lifters are the top hat type with a 7 degree release angle. The velocity vectors are super imposed on the balls and rock particles. A close look reveals within the cascade the central region where grinding action is minimum. Due to small release angle, considerable amount of rock and ball particles are thrown against the mill shell. The ball-to-liner strike zone extends as high as 9 O'clock mark. The mill may not reach design capacity, especially with hard ore type. Furthermore, considerable damage to liners is imminent within four months of operation.

Next, we consider the same mill fitted with 30 high lifters (and 30 low lifters) of 25 degree release angle. Figure 2b shows the snap shot of charge animation. Here, ball strikes on liners are seen nearly upto 8 O'clock position, a considerable improvement over Figure 2a. this lifter is suitable for maintaining a moderately aggressive charge motion at the expense of shorter lifter wear life.

Next, the release angle increased to 30 degrees with 30 high lifters (and 30 low lifters) whose animation is shown in Figure 2c. The cataracting charge lands within the toe of the charge. This type of charge motion is ideal for SAG, for it to preserve the lifters. The mill speed may be increased without fear of damaging liners. Alumbrera mines exploited this concept to increase production. With such lifters, Alumbrera even used 150 mm top ball size.

The most optimum charge profile is described in Figure 2d with dotted line. The mill is purposely fitted with 60 high lifters with 45 degrees of release angle. Also, the mill speed has been increased to 80% critical. The goal is to bring the cascading charge to take-up the position shown by the dotted line. If the lifters can lift the charge to 1 O'clock position, the rocks fall over a distance of one mill diameter at least. Thus, we fully utilize the mill diameter. However, while the shoulder of the charge is thus raised, the cataracting action should be as minimum as possible. To bring about such a charge motion, the mill filling must be 35% or higher. The lifter shown in Figure 2d did not achieve the target charge profile.

Industrial case studies SHELL LIFTERS
In recent years, with increasing mill size whose power draw has reached over 20MW, emphasis has been diverted towards the design of shell lifters to increase the grinding efficiency. Lifters

are not only consumables for protection against wear, but also critical machine elements. They transfer power to the mill charge and govern the pattern of energy distribution inside the mill, including affecting the grinding kinetics. The performance of liners changes with time, as their shape changes by wear. A good design must take these restrictions into consideration and optimize the performance of liners for the full duration of their useful life. The attainment of expected useful life of a set of lifters depend not only on their initial shape, material and quality of fabrication but a good matching between expected and real operating conditions inside the mill. The main issue is the direct impact of balls on the lifters in the absence of the damping effect of a bed of mineral ore and ball charge. In the following, the capacity increase achieved with newer shell lifter designs using Millsoft or other methods is discussed.

Collahuasi Mines, Chile is a 65,000 tpd operation. It employs two 32 X 15 ft variable speed SAG mills and four 22 x 36 ft ball mills. The original lifters had a face angle of 6 degrees and therefore the SAG mills suffered a throughput restriction. According to Marcelo Villouta (2001), plant manager, "the original SAG mill liner design, Hi-Hi with a 6 deg contact angle, was changed to a 17 deg face angle and then with Dr. Rajamani's (Millsoft code) assistance a new design, Hi-Hi with 30 deg contact angle was installed in SAG mills. A noticeable 11% increase in ore throughput was achieved.

Alumbrera Mines, Argentina (Sherman, 2001) is a copper ore operation treating between 70,000 to 100,000 tpd of ore depending on the rock type presented to mill feed. Two SAG mills of 30X15 ft are used in this circuit. The original design called for 72 rows of 9° lifters. These lifters resulted in drop in the capacity to 50,000 tpd. Within 6 months of start of operations a new lifter design was explored with Millsoft simulations. As a result, the lifter set was changed to 48 rows of 25° lifters and later to 36 rows of 30° lifters. These lifters increased the throughput steadily to 96,000 tpd. Even today, lifter design is constantly modified along with the use of larger size (6 " as opposed to 5.5 ") to increase production while processing hard ores.

Candelaria Mines, Chile is a 65,000 tpd operation. The grinding circuit includes two 36x15 ft SAG mills. The original lifters were 72 rows of rail design with 10 degree release angle. A year later the release angle was changed to 20 degrees. Another year later, the shell lifter design adopted was a 36 rows of 35 degree release angle. This design eliminated packing between lifters, throughput increased by 15%, the wear was slightly better than traditional lifters and the power draw in the first month was much higher compared to previous designs.

Los Pelambres Mines, Chile is 120,000 tpd operation. The SAG mill size is 36x17 ft. the first shell lifter design was 72 rows of 8 degrees release angle. However, severe packing was noticed which was the reason for lower capacity. Subsequently, Millsoft simulation software was used to explore better design. The new lifter design was 36 rows of 30 degree release angle. This design increased throughput by 10,000 tpd.

GRATE AND PULP LIFTERS

Recently, much attention has been focused on the grate/pulp lifter assembly, as the objective has been shifted to maintain very high throughput in closed circuit SAG mill operations. This has

emphasized the operational problems in removing high volumes of slurry and pebbles via the grates and pulp lifters.

The discharge of fine material through the numerous slots in the grate is poorly understood not because of any lack of physical methodology but due to the unpredictable events occurring in the vicinity of the grate. Balls and pebbles constantly cover up numerous slot openings and the slurry finds its way around the balls and pebbles. Furthermore, small pebbles permanently lodge themselves in these slots and at random times they dislodge. To release the larger sized pebbles, usually pebble ports, although fewer in number, are provided on the grate.

Pulp lifters (also known as pan lifters) are an important component of these mills whose function is to transport the slurry flowing through the grate holes into the discharge trunnion and out of the mill as shown in Figure 3. Although pulp lifters are obviously important in determining the ultimate discharge flow capacity, very little work has been reported either on their performance or on their influence on mill efficiency.
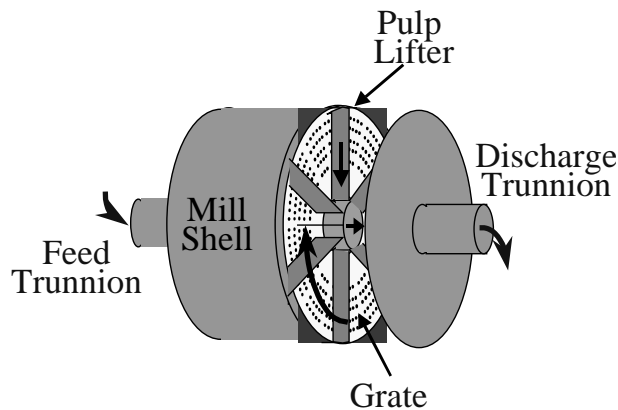

Figure 3 : Typical arrangement of Grate and Pulp lifters in SAG mills

The design of grate/pulp lifters in SAG mills has a substantial impact on the behavior of the mill. If sufficient grate open area and pulp lifter capacity is not available, they will provide a high resistance to flow of slurry resulting in excessive amount of slurry resulting in slurry pool formation inside the mill. If the amount of slurry exceeds a level past where efficient grinding occurs, the mill will "go off the grind" (Moys, 1986 and Austin et.al, 1984). Build-up of large volumes of slurry will have serious problems by reducing the effective density of the submerged media to a low level, which reduces the inter-media forces that are responsible for grinding of finer particles. The presence of slurry pool tends to reduce the power draw and grinding performance.

Performance of pulp lifters

A detailed investigation by Latchireddi (2002), Latchireddi and Morrell (1997, 2003a and 2003b) on impact of the discharge grate and pulp lifters on slurry transport in SAG mills revealed the limitations of the conventional designs of pulp lifters (Radial and Curved) on slurry transport in SAG mills. The performance of pulp lifters in transportation of slurry passed through the

discharge grate are illustrated in Figure 4. For an efficient slurry transport though the mill, the discharge capacity of pulp lifters should match with the discharge capacity of grate-only at any given slurry hold-up.
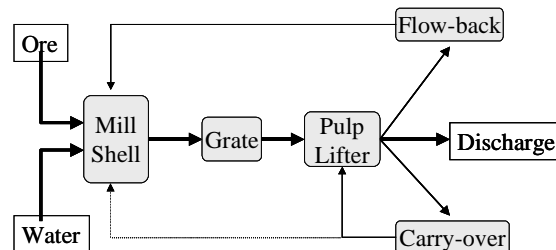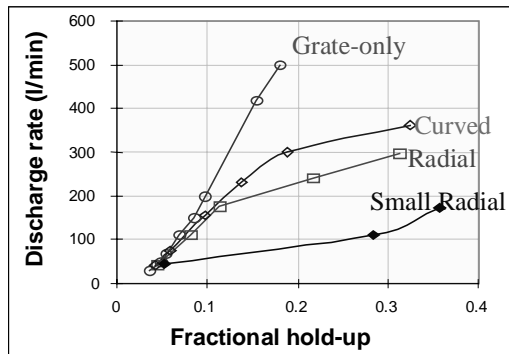

Figure 4: Flow of slurry through grates and pulp lifters; Figure 5: Process of slurry transportation in SAG mill

The reason for the significantly inferior performance of the conventional pulp lifters is the Flow-back phenomena. The flow-back of slurry from pulp lifters into the main grinding chamber through the grate can be as high as 60% depending on the design and size of the pulp lifter assembly. The fraction of slurry remained in the pulp lifter gets carried over to the next cycle as carry-over fraction, however, this occurs in mills operating at higher speeds. The overall slurry transportation process in AG/SAG mills is summarized in Figure 5.

The excess slurry due to flow-back process accumulates near the toe region resulting in slurry pool formation (Figure 6). This slurry pool softens the ball strikes at the toe of the charge, which inhibits the impact breakage of particles. It also diminishes the shearing action in the cascading charge, which reduces the fine particle grinding. Both these aspects adversely affect the grinding efficiency thus reduce the mill capacity. Furthermore, the slurry pool applies a counter torque in the mill effectively reducing the power draft. Therefore, the operator either increases the feed rate or increases the critical speed to increases power draft, the power draft increases at first but decreases later, thus giving a false indication.
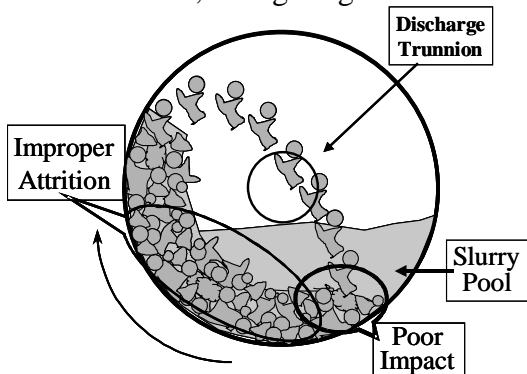

Figure 6 : Adverse effect of slurry pooling on grinding process in SAG mill

Pebbles motion in Pulp Lifters

Efficient removal of the pebbles (up to 70 mm in size) by pulp lifters is an important aspect of pulp lifter design, which can reach up to 1000 tph in a large diameter SAG mills. The principle and technique used in the design of shell lifters using DEM can be effectively used to study the pebbles and slurry flow in pulp lifters. Instead of the continuum approach the slurry is also modeled as discrete spherical particles with properties of fluid. These particles are combined with rock and ball particles to do the simulation. Simulations were carried out to visualize the ability of different pulp lifters in discharging the pebbles in to the discharge trunnion at desired mill speed.

The simulation conditions tested here for a mill of 34 ft in diameter with discharge trunnion diameter of 8.5 ft. The number of pulp lifters used was 40 with a depth of 300 mm. The mill speed was set to 70% critical speed.

The output of the simulations for the most commonly used radial pulp lifter (RPL) is shown in Figure 9 showing the snapshot-a of the position of pebbles at the beginning of the pebbles moving into the discharge trunnion and snapshot-b showing the pebbles remaining inside the pulp lifter after completion of discharge or 9 O'clock position. It is apparent from Figure 9 that the pebbles of 60 mm are unable to get discharged completely into the discharge trunnion by the RPL. A large number of pebbles remain inside the pulp lifters and gets carried over. It is obvious that with increase in mill speed more number of pebbles would remain un-discharged.

Radial

(a) beginning of discharge   (b) pebbles remained in pulp lifer
                                    after one revolution
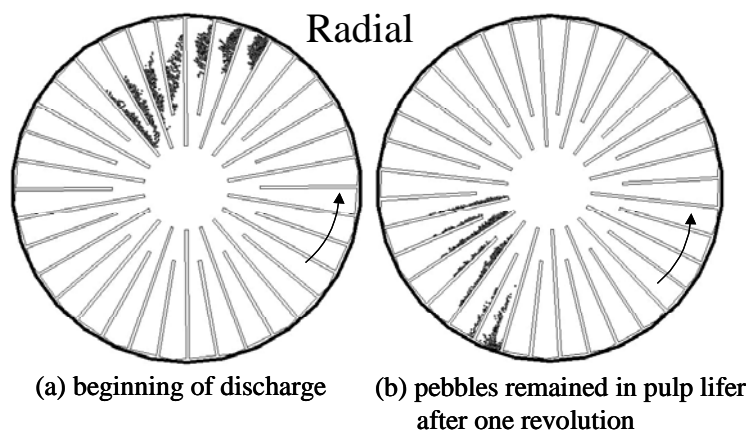
Figure 9: Flow of pebbles in radial pulp lifters

The snapshot of the pebbles motion in curved pulp lifters (CPL) are shown in Figure 10. Compared to the radial pulp lifter (Figure 9), the curved pulp lifters (Figure 10) discharge the pebbles (60.5mm) more efficiently. A small number of pebbles remain inside the pulp lifters at 74% critical speed. However, when the pulp lifter size is increased to 500mm, almost all the pebbles were successfully discharged.
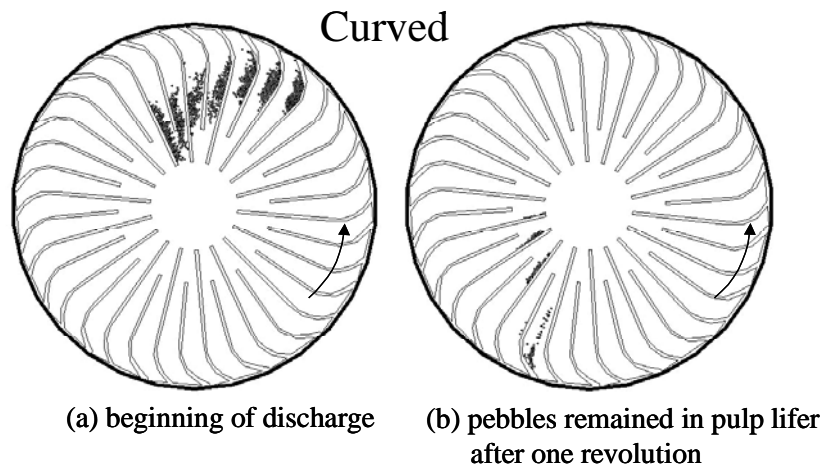
Curved

(a) beginning of discharge   (b) pebbles remained in pulp lifer
                                     after one revolution

Figure 10: Flow of pebbles in curved pulp lifters

CONCLUSIONS

It is shown that the design of both shell lifters and grate-pulp lifter assembly are very important for optimal performance of the ag/sag mills. The discrete element numerical method is an ideal tool for modeling semiautogenous mills. In particular, power prediction of a plant scale mill was shown. Furthermore, the method can be adapted for the simulation slurry flow through grate and pulp lifters. Simulations show when potential back flow into the mill occurs.

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Shell and Pulp lifter study at the Cortez Gold Mines SAG mill

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ABSTRACT

The energy efficiency of these high-throughput grinding mills can be attributed to the field of breakage and slurry transport. The charge motion and breakage of particles inside the mill depends on the shell lifters design, while the discharge of ground particles is controlled by the grate and pulp lifters. The design of these mill components has been largely based on trial and error and hence varies considerably between manufacturers. This paper discusses the use of two state of the art design tools - Millsoft™ and FlowMod™. Millsoft™ is an effective tool to design the shell lifters and optimize charge motion, whereas FlowMod™ simulates the slurry discharge system to design grate and pulp lifters. A study done at the Cortez Gold Mines SAG mill shows how the redesign of the shell lifter brings about a reduction in energy consumption when slurry transport through the mill is adequate.

INTRODUCTION

There are a number of SAG mills in operation around the world whose diameter reaches up to 40 ft. These operations continually invest in new technologies to improve their energy efficiency and capacity in their SAG circuit. Commercial SAG mill performance is determined by a large number of variables, both mine site variables and mill variables. In many cases these variables dictate production capacity seemingly randomly. Therefore a number of operating philosophies, each specific to a plant, have arisen. In almost all concentrators the SAG operation is a continually evolving operation. Every year, ways and means are sought to increase capacity, decrease energy consumption and prolong lifter and liner life. Ore blending, newer design of lifters, recycle crushing and redesign of grates and trommel screens are a few routes taken at considerable expense.

Operation of SAG Mills

The processing capability of a semi-autogenous (SAG) mill is greatly affected by ore geology and operating variables within the mill. The key issues can be broadly classified in to two categories: field of breakage/ charge motion and flow through the grate and pulp lifters. The field of breakage and charge motion are primarily affected by the design of shell lifters and mill speed. Once the ore is ground to a size that can pass through the grate holes, the slurry flows into the pulp lifter chamber that transports into the discharge trunnion. These components of the SAG mill are schematically shown in Figure 1 for easier understanding.
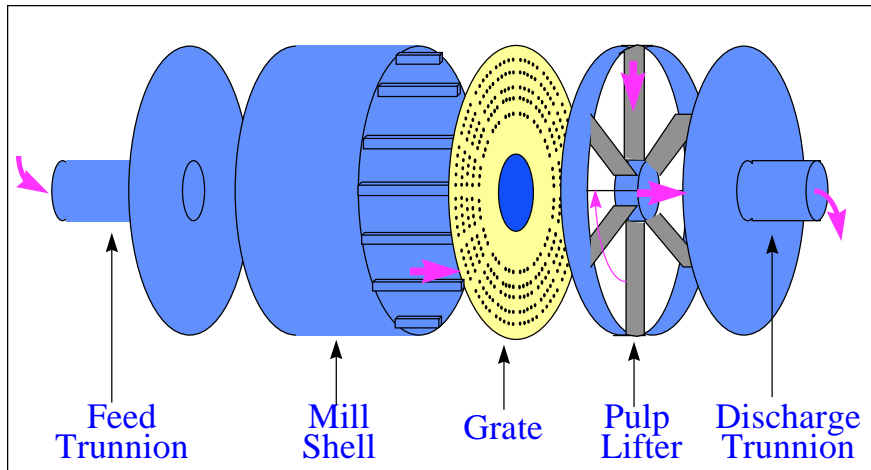
Figure 1 : Schematic of a typical SAG mill.

Once the slurry has made its way via the grinding media charge, its first stage of discharge is via the grates. Hence in the absence of any subsequent restriction the maximum flow capacity that can be obtained for a given mill is determined by the grate design. Here the design variables are open area and radial distribution of slots. The driving force for slurry transport from the mill shell through the grate holes is the difference in pressure head across the grate.

Field of breakage: The motion of charge or rocks and balls in SAG mils can be viewed as a field of breakage generated as a result of the internal profile of the lifters and the rotational speed of the mill shell. The ore entering through the feed port is ground by this field and, after being sufficiently ground to the grate slot size, the slurry leaves through the slots in the grate. The field of breakage influences the rock mass in the SAG mill. Should the incoming ore be harder and the field of breakage insufficient to reduce the size, the ore stays in the mill longer since it is unable to pass through the grate. The net effect is an increase in rock mass, and the feed rate to the mill must be decreased appropriately to maintain rock to ball ratio. On the other hand, when the ore is soft, the field of breakage reduces the ore size rapidly and hence the rock mass decreases. To sustain a set rock mass, the feed rate must be increased. The complicating factor is that the incoming ore feed itself determines the breakage field.

Flow through the grate and pulp lifters: Discharge grates and pulp lifters play an important role in performance of the autogenous and semi-autogenous mills [4]. The performance of the pulp lifters in conjunction with grate design determines the flow capacity of these mills. The function of the pulp lifters is simply to transport the slurry passing through the discharge grate into the discharge trunnion. Its performance depend on the size and design, the grate design and mill operating conditions such as mill speed and charge level. The difficulties associated with slurry transportation SAG mills have become more apparent in recent years with the increasing trend to build larger diameter mills for grinding high tonnages. This is particularly noticeable when SAG mills are run in closed circuit with classifiers such as fine screens or hydrocyclones.

The performance analysis of conventional pulp lifter designs shows that a large amount of slurry flows back from the pulp lifter into the mill [5-8]. The flow back depends on the size and design of the pulp lifters. Since the back face of the pulp lifter is the grate itself, the slurry readily flows

back into the mill. Subsequently, the field of breakage diminishes when excessive slurry builds in the mill.

Charge motion: In a concentrator, all of the auxiliary equipment-pumps, conveyers, screens and hydrocyclones - and two primary resources-steel and electricity-serve primarily to maintain grinding action in the belly of the SAG mill. It is this action that dictates capacity. This being the case, it is understandable to observe this grinding action continuously from the control room and take whatever steps are necessary to keep the grinding field at its highest potential. Unfortunately, the grinding environment within the mill shell is very severe and none of the on-line instrumentation developed so far is able to survive the continuous impact of large steel balls. Since direct observation is impractical, the next available option is a simulation of the grinding field to gauge the intensity of grinding or lack of intensity of grinding.

Mill power draft: The field of breakage and flow through grates and pulp lifters influences each other and the net effect is the build-up of a hold-up level in the mill, which draws a certain power and this power draft is clearly linked with mill throughput. If the interaction can be understood then mill capacity can be understood much more clearly. Then the expectation of increasing capacity at the same level of power draft by one means or another can be safely evaluated.

The power draft of a SAG mill and its consequences are illustrated in Figure 2, wherein five days of operating data in a 32x14 ft SAG mill is plotted. The power draft of the mill is held between 6 and 7 MW, whereas tons per hour (TPH) of ore feed to the mill shows wide variations between 1000 tph to 1600 tph. When closely examining Figure 2, one finds that the feed rate drops whenever the power draft shows an increasing trend, whereas intuitive reasoning says that feed rate should be proportional to power draft.

The data shows that the specific energy consumption (kWh/tonne) of ore is not steady, as one would expect for a typical ore body. Even within a 24-hour time frame, where the feed ore hardness may be assumed constant, the variation in feed rate is drastic. The internal dynamics within the SAG mill, as exemplified by the three broad concepts, are causing wide fluctuations in grinding rate, which in turn is reflected as capacity.
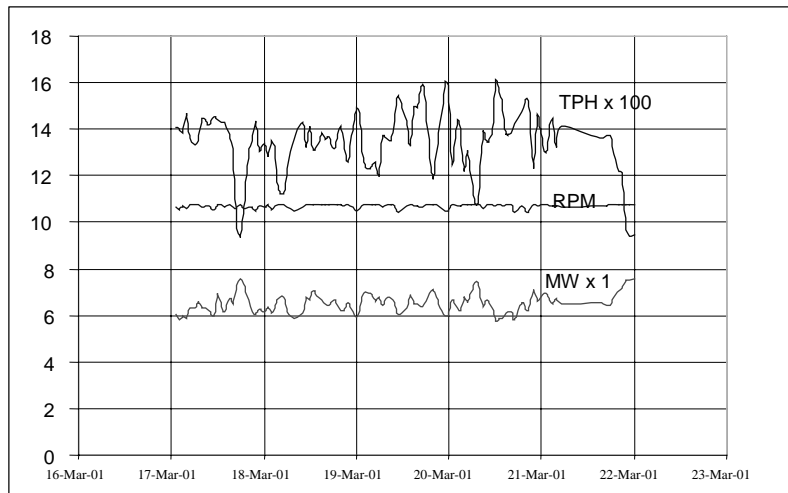
Figure 2: Five days of plant operating data: 32x14 ft SAG circuit.
(TPH-fresh feed rate, MW-mill power in megawatts)

SAG Mill Efficiency

The energy efficiency of tumbling mills can be directly examined by looking at the motion of ore and grinding balls inside the mill. The make-up of the charge and the lifter bars attached to the inside of the mill shell can be designed particularly to maximize the mass of ore fractured per unit of energy spent. At the same time, the unnecessary collisions of steel balls against the mill shell can be reduced. Furthermore, the cascading charge flow can be altered in such a way as to maximize grinding efficiency. First, the shell lifters are designed in such a way the motion is fully cascading and that part of cateracting motion is made to strike in the vicinity of the toe. In such a charge motion regime both shearing action and impacts are fully utilized in grinding the ore.

The shell lifters are usually replaced once or twice a year. Pulp lifters survive two or three years. The design of these two important mill components has been largely based on trial and error and hence varies considerably between manufacturers. However over the years, important tools such as Millsoft™ and FlowMod™ have begun to help the designers to analyze and understand the influence of the internal components of SAG mills – shell lifters, grate and pulp lifters respectively. The following sections will discuss the basic principles and application of these two simulators.

Millsoft™ - Discrete Element Simulation of SAG Mills

The SAG mill is made up of cylindrical shell with two conical shells attached on both ends. Lifter elements are attached in both the cylindrical and conical shell sections. As the SAG mill rotates, typically around 10 rpm, the internal flat walls of the lifter and shell imparts momentum to balls and rocks. The momentum is primarily transferred to particles in direct contact with the plate elements [9]. These particles in turn impart their momentum to adjacent layers of particles. In this manner the motion of the entire charge evolves resulting in what is commonly referred to as cascading and cataracting charge.

The discrete element method embedded in MillSoft™ replicates the evolution of charge motion as described above. In the simulation the exact dimensions of lifters, plates and balls are used.

MillSoft can be used affectively to show the effects of different lifter configurations, mill loading, mill speed, and other operating conditions. Unlike single-particle trajectory programs which show only the outer most particle path, MillSoft takes into account the entire charge, one can effectively see the "kidney" shape of the charge, the dead zone, toe and shoulder of the charge, and areas of high-impact on the mill lifters.

Millsoft can also be used to follow lifter wear, shell plate wear and particle breakage. Most importantly, the location and the intensity of impacts on lifter bars can be computationally recorded and a corresponding metal abrasion at that location can be worked out. In a like manner, the energy of impact can be used to fragment the rock particles in the simulation. However, the distribution and number of fragments produced overwhelms the computational task and hence this computational path is rarely followed.

Shell lifter design and charge motion analysis with Millsoft™

A typical example of charge motion analysis with Millsoft™ is illustrated in this section. The SAG mill under consideration is a 38x24 ft mill drilled for 60 rows of shell lifters. Therefore, the mill can be fitted with 30 high and 30 low lifter sets or a total of 60 high lifters. The total charge is 27% with 15% balls. The mill is expected to draw 15-18 MW power. The mill speed is set at 76% critical speed. The snapshots of the charge motion at different conditions are shown in Figure 3.

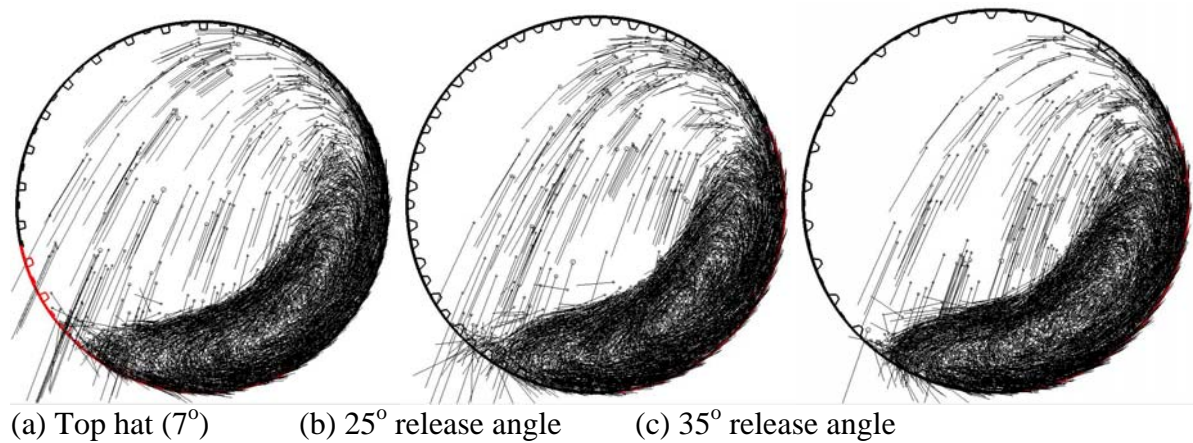(a) Top hat (7°)   (b) 25° release angle   (c) 35° release angle

Figure 3: Snap shots of charge motion.

Figure 3a shows the SAG mill fitted with traditional lifters. The high lifters are the top hat type with a 7-degree release angle. The velocity vectors are super imposed on the balls and rock particles. A close look reveals within the cascade the central region where grinding action is minimum. Due to small release angle, considerable amount of rock and ball particles are thrown

against the mill shell. The ball-to-liner strike zone extends as high as 9 o'clock mark. The mill may not reach design capacity, especially with hard ore type. Furthermore, considerable damage to liners is imminent within four months of operation.

Next, we consider the same mill fitted with 30 high lifters and 30 low lifters of 25-degree release angle. Figure 3b shows the snap shot of charge animation. Here, ball strikes on liners are seen nearly up to 8 o'clock position, a considerable improvement over Figure 3a. This lifter is suitable for maintaining a moderately aggressive charge motion at the expense of shorter lifter wear life.

Next, the release angle increased to 35 degree with 30 high lifters whose animation is shown in Figure 3c. The cataracting charge lands within the toe of the charge. This type of charge motion is ideal for SAG, for it to preserve the lifters. The mill speed may be increased without fear of damaging liners. Alumbrera mines exploited this concept to increase production. With such lifters, Alumbrera even used 150 mm top ball size.

SAG MILL STUDY AT CORTEZ GOLD MINES

The aforementioned analysis of shell and pulp lifters is illustrated with the work done at Cortez Gold Mines, Crescent Valley, Nevada. The grinding circuit consists of a 26X17 ft. SAG mill in closed circuit with a pebble crusher. The discharge of the SAG mill is screened on a 0.75-inch screen and the oversize material is fed to the cone crusher. The undersize is sent to the ball milling circuit. The typical SAG mill feed is 400 stph, which varies anywhere between 250-550 stph, depending on the ore-type. At least five different ore types are encountered at this mine site.

Over many years the SAG shell lifter has evolved to a high-low pattern with a typical high lifter dimension of 7-inch height, 5-inch wide at the top and 17^0 face angle on both sides. The low lifter dimensions are: 5-inch height, 5-inch top width and 17^0 face angle on both sides. The mill shell has been drilled for 52 rows of shell lifters. The open area of grate is 7% with the typical 2.75-inch square opening.

The plant operating work index shown in Fig.4 shows an increasing trend. Over a 2-year period the index increases from 13 kWh/st to 16 kWh/st. The plant estimates a 5% increase in the power draw of the SAG mill during the same period.
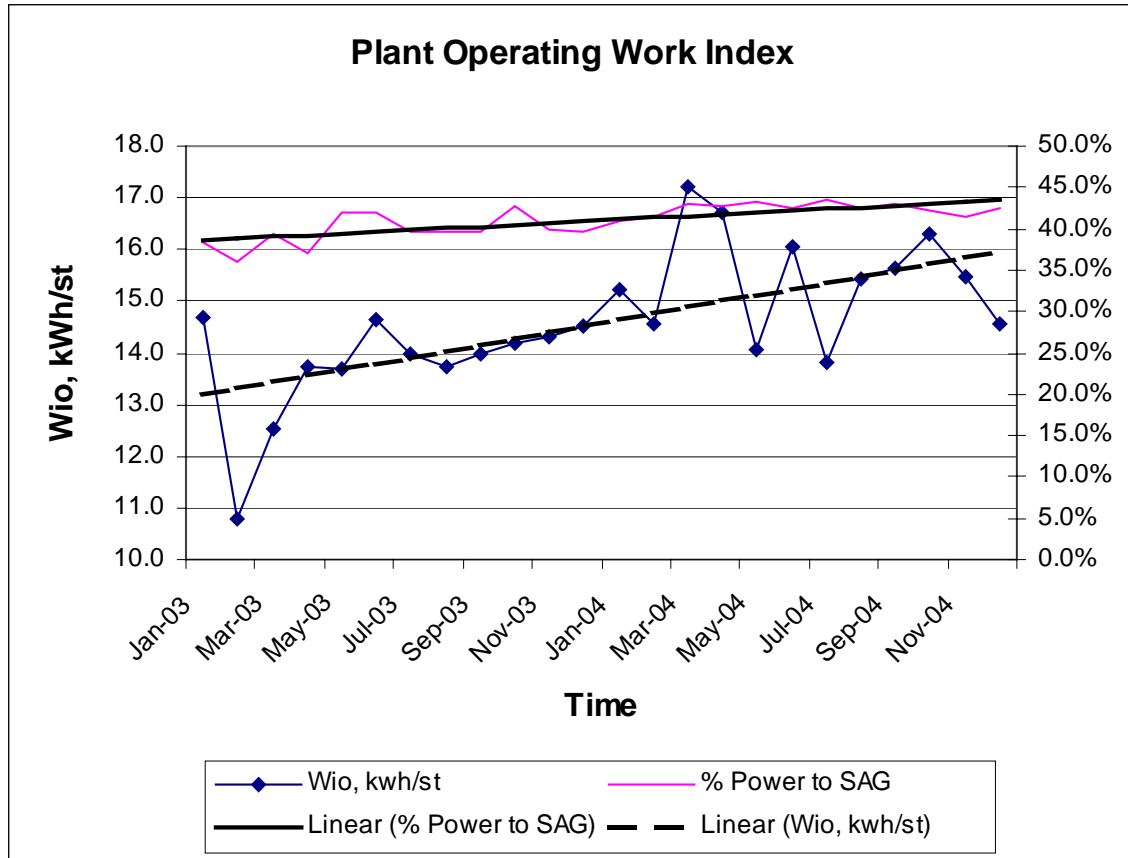
Plant Operating Work Index

Figure 4:

Grate and pulp lifters: First, a review of the grate plate and pulp lifter showed that 7% open area was adequate for handling the daily-targeted tonnage. In fact, the grate openings were found to be free of balls or rocks during many inspections. The discharge capacity of the grate is 482 m³/hr of slurry. However, FLOWMOD calculations indicated that the pulp lifter diminished this flow to 382 m³/hr as a result of flow back phenomena. However, this flow rate is adequate to handle current daily tonnage. Also, the radial distribution of grate opening in the mill periphery indicated that some advantages could be gained by redistributing the open area in the most optimal flow regime. The recommendation was implemented in a subsequent grate redesign. In summary, the grate and pulp lifter combination was operating more than satisfactorily although there is always room for further increase in the pulp discharge capability of the mill.
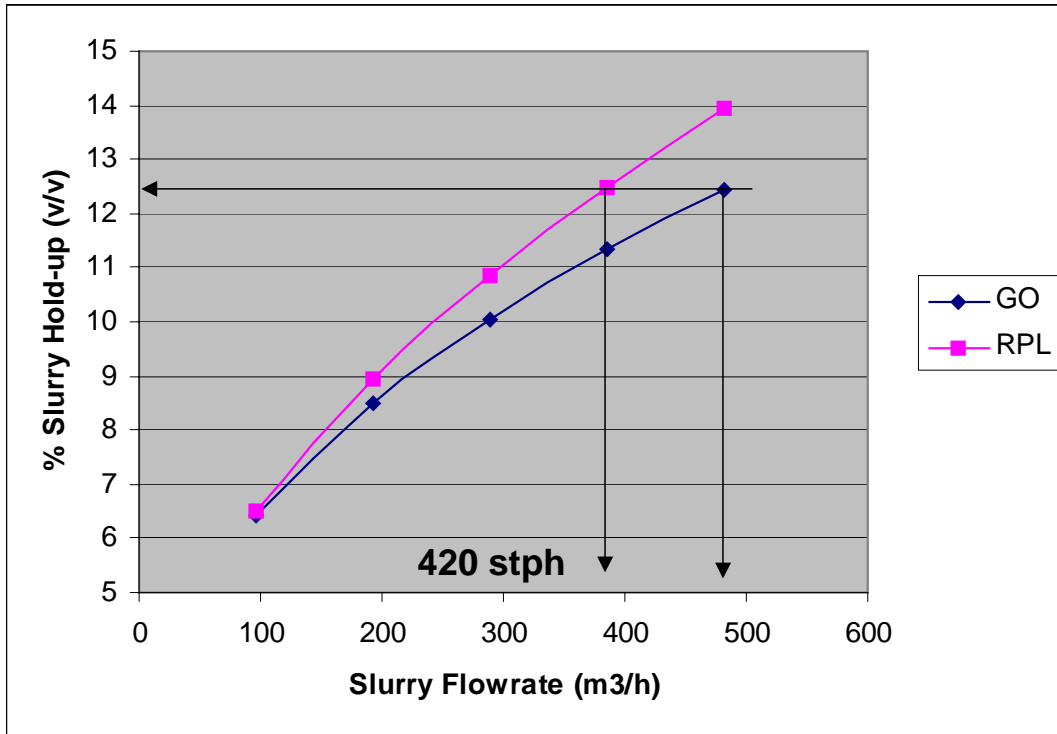
Slurry Removal Efficiency of PL (SREPL)= 382.65/481.88 = 79.4%

Figure 5 :

Figure 5 shows discharge flow rate as a function of fractional slurry hold-up. At the current operating conditions, increasing the open area to 9% and redistributing the slots radially may increase the discharge flow rate to 450 m3/hr.

It is very critical that the pulp transport capacity of the mill must be set at its maximum value before changing shell lifters. The shell lifters may increase the production of fines, but there must be the capacity to discharge these fines.

High-low shell lifter experience: The high-low shell lifter design leaves a gap of 10 inches between the lifters. As a result, caking between lifters was very severe. Due to cake build-up the effective height of the high-lifter over the base is a mere 2-inches. Figure 6 shows the MILLSOFT simulation of charge motion with the high lifters. The 17^0 lead face angle causes cataracting between 8 o' clock and 9 o' clock positions of the mill circle.
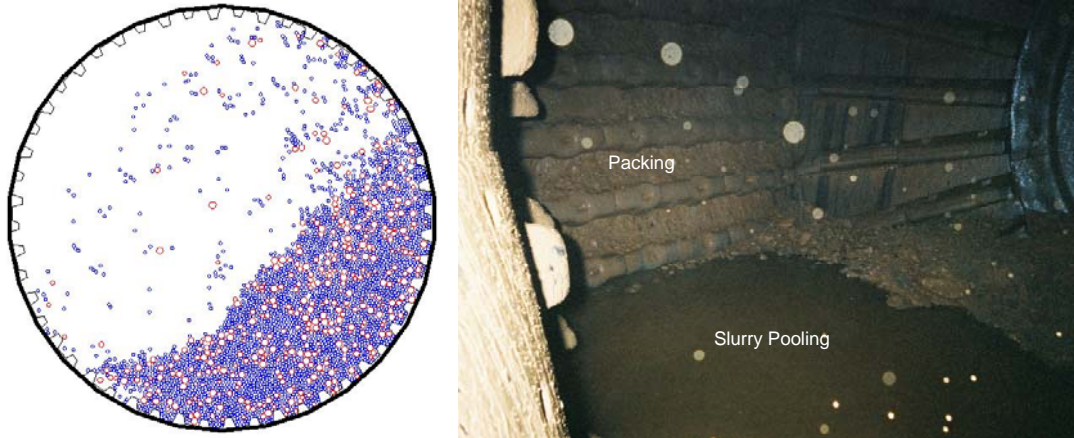
Figure 6: Charge motion with high-low lifters

With the use of 5-inch grinding balls and exposed shell plates the cataracting caused consistent and moderate level damage to the mill shell. Some of the lifters were broken and in other places there was severe peening. As a result the mine experienced unscheduled SAG mill related down time every month. Figure 7 shows the unscheduled down time for a two-year period. It is seen that even as the lifter is in the last four months of operation leading up to September 2004, there is down time due to lifter damage. Crash stop done during this period shows cake build up between lifters and a fair amount of slurry retention within the mill.
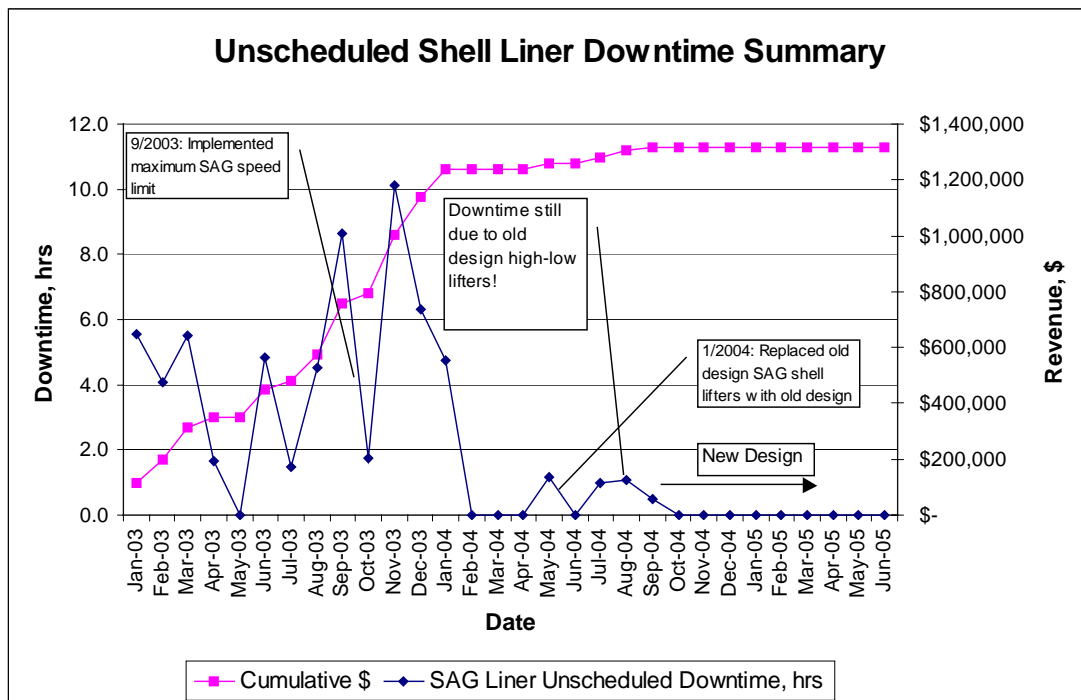

Figure 7: Unscheduled downtime

Shell lifter redesign: A decision was made to reduce down time and increase energy efficiency with a new design of lifters. In particular, it was decided to bring the 5-inch ball trajectory to the toe of the charge by correct choice of leading face angle. Furthermore, it was decided to eliminate every other lifter row to minimize packing and maximize lift as well as increase mill volume. Figure 8 shows Millsoft simulation of the new design (9 inch height, 5 inch top width with 28° leading and trailing face angle). As anticipated the cataracting charge lands near the toe of the charge at around 7 o' clock position of the mill circle. The simulated power draw was consistent with operating power draw. This type of liners with leading face inclined at a steep angle (22°-35°) has been well documented in the literature. A number of mine sites, including Alumbrera [11], Collahuasi [10], Candelaria, Los Pelambres and others[1] have had success with these lifters. Besides the design criteria for optimal trajectories for 5 inch grinding balls a number of other issues such as safety of liner handling, safety of mill noise, inching drive capability, load on the mill motor and mill start-up had to be addressed and taken care off.
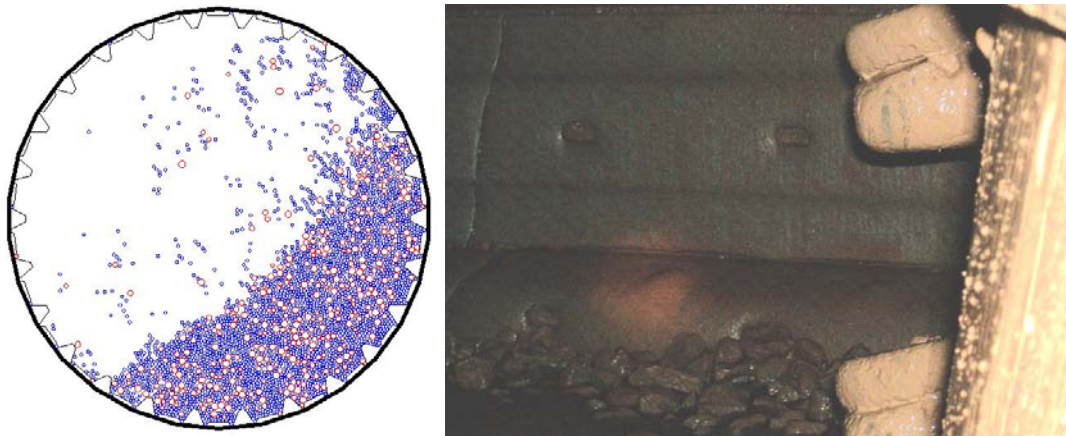

Figure 8: Charge motion with new lifters

The new design installed in September 2004 had 33% less pieces but each piece was 2.5 times heavier than previous liners and hence the liner handler capacity had to be increased. Mill noise is certainly an issue, but with steeper angle it was expected to be lower. Actual noise measurement upon installation showed a 2% higher noise, which is attributed to elimination of packing between lifters. There was also the issue of inching drive which had to work against a higher load, especially during liner installation. Mill would be most unbalanced when half the set of liners are installed during liner installation. Therefore the inching drive power rating was increased. The design added 41 extra tons to the mill shell. Therefore the issue of mill bearings being able to handle the extra weight and extra motor horsepower to sustain mill operating rpm were addressed.

Slurry transport and load build-up in the mill: Slurry transport out of the mill plays an important role in determining SAG capacity. Figure 9 shows the cyclical behavior of the SAG circuit three weeks after change over to the new lifter design. In particular the feed to the SAG mill cycles up and down in every two hours. Mill bearing pressure exhibits similar behavior. The cyclical behavior is primarily due to pulp lifter returning part of the slurry passing through the grate back into the mill. In other words back flow in the pulp lifter returns part of the slurry to

the mill. As a result the mill slurry hold-up increases and the controller cuts the feed to the SAG mill. This cyclical behavior points that the circuit capacity can be improved by a proper choice of pulp lifters [2].
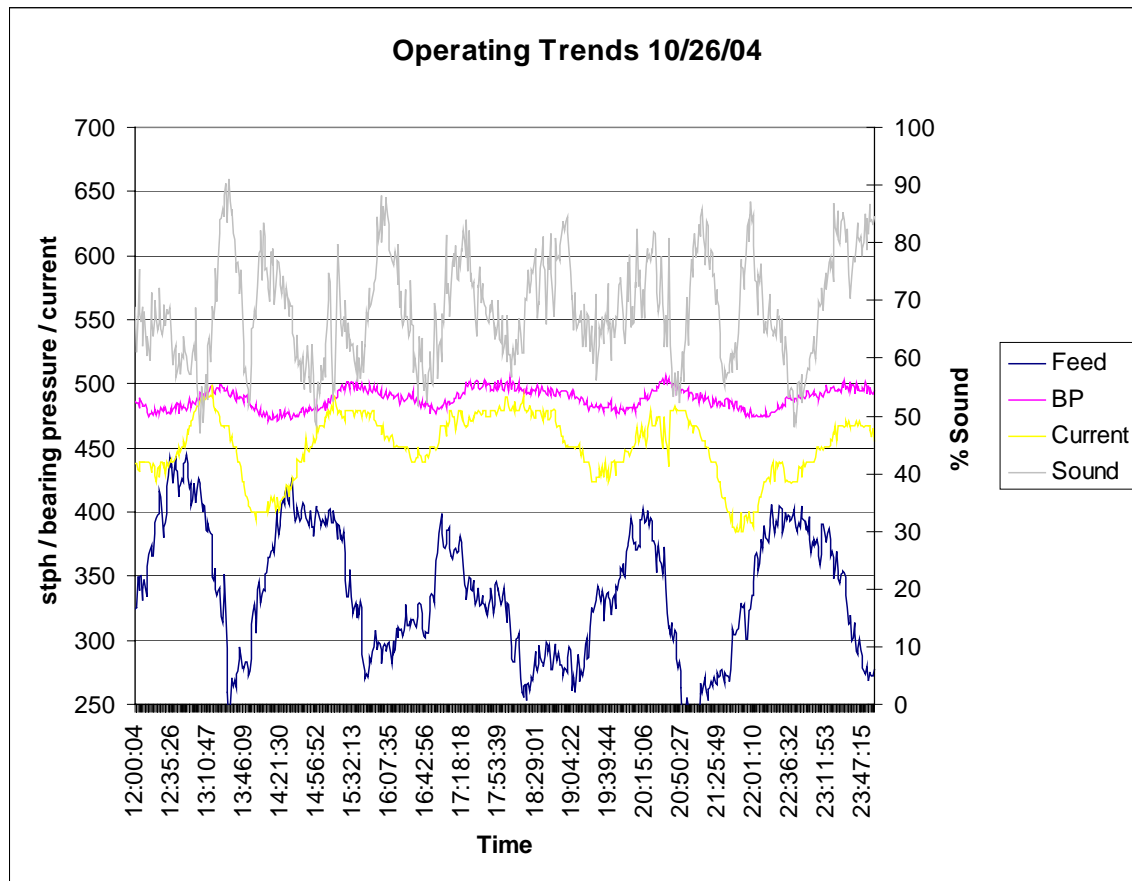

Figure 9: Cyclical behavior of the mill

Impact on power draw and energy consumption: The main focus here is the energy efficiency of the SAG mill. Figure 10 shows the SAG throughput before and after installation of new shell lifter. The SAG circuit maintains more or less the same throughput after lifter installation. It should be kept in mind that ore type is changing from day to day and it will take over 4 months to encounter all different ore types. The major advantage gained with the new lifter design is shown in Figure 8. The SAG mill is showing definitive reduction in power draft after installation. It is estimated that the power decreases is in the 230-370 kW range. Hence energy consumption per ton of ore milled has decreased by 0.3-1.3 KWH/ton. Furthermore 1-10% reduction in recirculation to the cone crusher was noticed due to efficient impact breakage of critical size material. All of these amounts to a significant operating cost reduction.
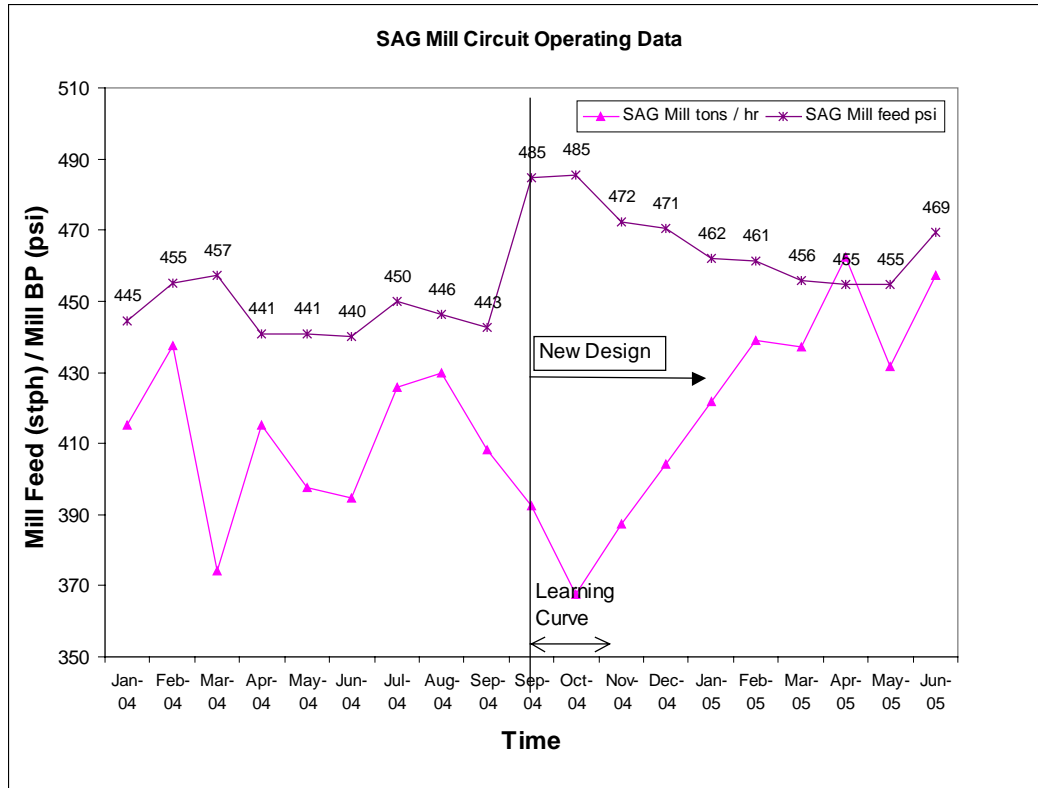
Figure 10: SAG mill operation before and after installation of new shell lifters.
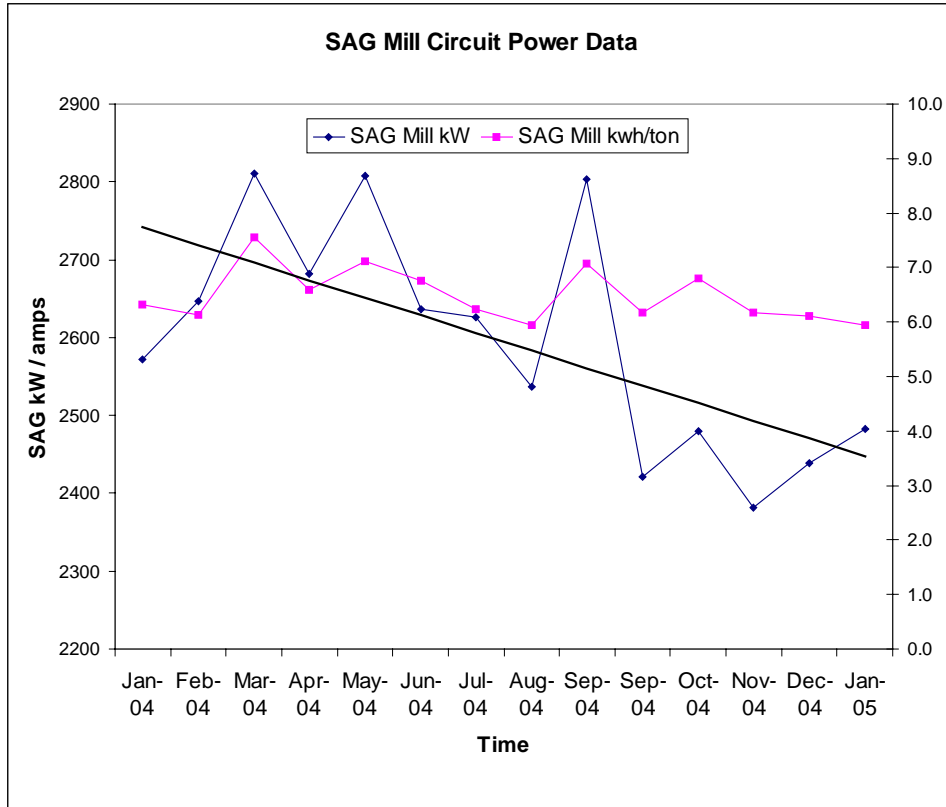
SAG Mill Circuit Power Data

Figure 11: SAG mill power data

A more efficient ball trajectory or charge motion means that there is less of direct impact of grinding ball on shell plates and lifters. As a result grinding ball consumption and steel losses in lifter wear must be impacted. At Cortez Gold Mines operation grinding ball consumption could not be tracked via digital control system. However, it was noticed that in 16 weeks of operation only 2.5 inches of lifter height was lost due to wear. It was estimated that the new design costs 57kgs/day of steel loss compared to 84kgs/day for the previously installed lifter, a 47% savings in steel loss. Furthermore, in the 9 months of operation leading upto June, 2005 the mill did not experience any down time due to cracked shell plates, severely peened lifters, broken lifters or leaky bolts. Thus we find that proper design of shell lifters leads to a decrease in energy consumption per ton of

CONCLUSIONS

It is shown that the design of both shell lifters and grate-pulp lifter assembly are crucial for optimal performance of the SAG mills. The design of shell lifters, which control the charge motion thus the breakage field, can be optimized using Millsoft™ - a discrete element numerical method. FlowMod™ is a steady state simulator to optimize the design of grate and pulp lifters to handle the given flow through the mill. It estimates the slurry hold-up inside the mill and shows

its dynamic surface at any mill operating condition. These two tools were employed in the study of the SAG mill at Cortez Gold Mines. First the flow or discharge capacity of grate and pulp lifter were analyzed. It was found that the capacity is adequate for meeting daily tonnage. Next, the redesign of shell lifters readily resulted in 230-370 kW reduction in mill power draw while maintaining the same throughput level. The SAG mill circuit exhibits cyclic loading behavior indicating that there is room for further increase in capacity via pulp lifter redesign.

ACKNOWLEDGEMENT

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SAG Mill Operation at Cortez:
Evolution of Liner Design from Current to Future Operations

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ABSTRACT

The Cortez SAG mill liner design was recently modified to improve the mill operating energy efficiency. In addition to the expected benefits, the design change unexpectedly played a significant role of verifying the proposed grinding circuit expansion for the Cortez Hills project as well as illustrating current SAG mill bottlenecks. This paper will discuss the evaluation that addressed operator and maintenance observations, historical PLC data, and "crash stop" observations to calculate charge motion, packing between lifters, and slurry transport through grate and pulp lifters. The performance of the new shell and discharge end liner design will also be discussed as well as their role in the possible grinding circuit expansion.

INTRODUCTION

Cortez Gold Mines commenced operation in 1969 with its Mill #1 rated at a nominal 2,000 tons per day. Mill #1 was a conventional rod mill/ball mill circuit followed by an 8-stage CIP circuit. In the early 1990s the Pipeline deposit was discovered and subsequently Mill #2 was built to process the increased ore volume. Mill #2, commissioned by mid-1997, was a nominal 10,000 tons per day SABC circuit followed by an 8-stage CIL circuit for oxide gold ore. Operating and commissioning details of this plant have been published elsewhere (Powell, 1998). By late 1998, there was not enough ore volume to support both mills so the smaller, higher operating cost Mill #1 was put under its current care-and-maintenance status. A simplified flowsheet of the current mill is shown in Figure 1.
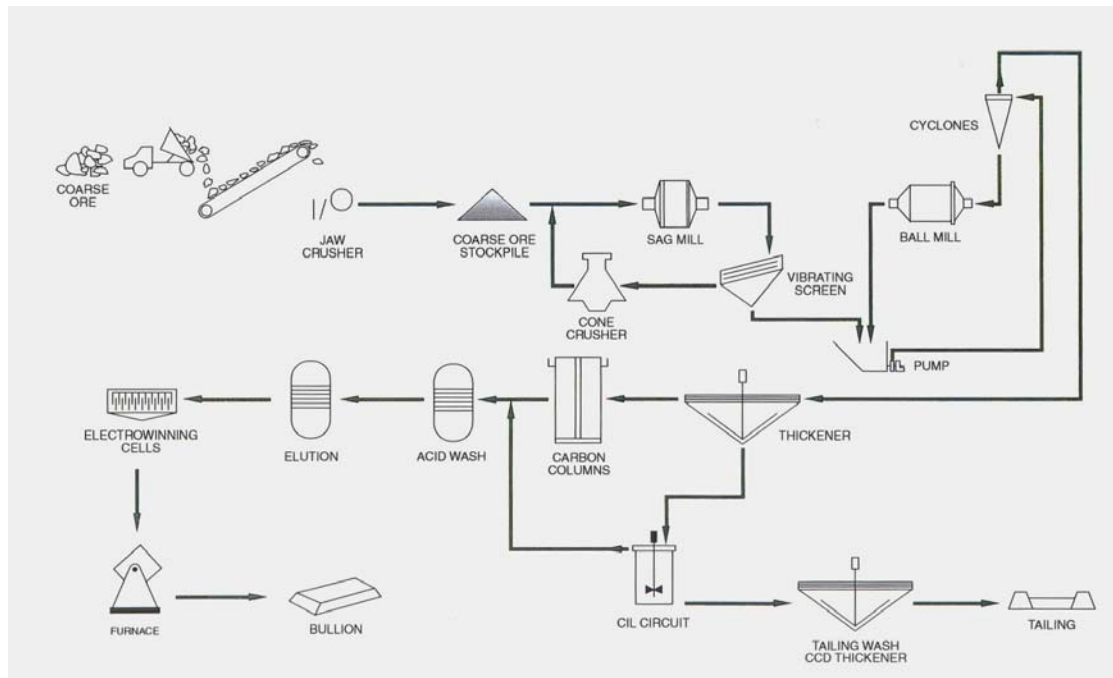
Figure 1: Cortez Gold Mines Mill #2 Flowsheet

The SAG mill is 26' diameter x 12'3" EGL and powered by 4,500 HP motor driven by a variable speed LCI drive that can control the mill speed from 36% to 80% of critical speed depending on ore type and operational demands. Ball charge is typically 8-12% and is adjusted accordingly after monthly mill inspections. Total mill filling is about 25%. The mill lining originally consisted of rubber plates and "polymet" lifters on the feed and discharge ends as well as rubber plates and cast lifters on the mill shell. The shell lifter pattern was 52 rows of high-low pattern (nominal 7" lift followed by 5" lift above shell plate) built with a 17° face angle. The grate open area was nominal 7% generated from 2.75" x 2.75" square holes. 5" grinding balls are also used. The maximum grinding circuit throughput as dictated by downstream conditions is about 13,500 dry tons per day (560 dtph).

Early in the Mill #2 life the ore had been predominantly ball mill limiting in that the ore basically "blew through" the SAG mill due to its already small size. Regardless of this, budget throughput targets that surpassed the original plant design figures were consistently being met. As such, focus on improving SAG mill performance has been limited except in the areas of liner wear life optimization. As Cortez progressively mined deeper into the pit in 2003 and early 2004 the ore generated a steadily increasing plant operating work index. The ore in turn started swinging towards SAG mill limiting. Slowly budget tons were just barely being met or just falling under targets. Difficulty in meeting targets was also being compounded by shell liner repair downtime induced by the aggressive ore that was also making its presence known in upstream process areas (e.g., crusher linings) via less wear material life.

In mid-2003 Cortez was approached by the University of Utah for participation in a voluntary U.S. Department of Energy (DOE) project. The primary tools that were used in this project were the MillSoft™ and FlowMod™ software packages after the collection of good plant operating data to calibrate the software.   In the initial stages of the project it soon became readily apparent that significant opportunities existed to improve on mill operating energy efficiency as well as improve on liner maintenance for improved productivity. Results from this study were also used in the mill expansion feasibility study for the Cortez Hills deposit and helped to concretely identify significant SAG circuit bottlenecks that should be addressed to maximize the current installed circuit as well as the possible future mill expansion to 15,000 tons per day.

SAG MILL CRASH STOPS

After the project was approved baseline data collection was required in the form of SAG mill "crash stops". In a crash stop the SAG mill is operated under steady-state conditions and then stopped as if the power plug was pulled. After mill lock-out and confined space procedures are satisfied researchers enter the mill discharge trunnion and take measurements and pictures of mill filling, ball load, slurry pooling, and liner wear observations. The mill is then restarted and then can continue under normal operation or be ground out for further ball charge and liner measurements. Cortez management was initially apprehensive about doing crash stops due to the downtime required. This was a valid concern, but the project team at the same time felt that a snapshot of our SAG operating under steady state conditions was necessary for the project success. After some negotiating, approval was granted, the Safety, Electrical, Mill Maintenance, and Mill Operation departments were coordinated, and the first crash stop was done just prior to a scheduled mill shutdown to minimize downtime.

Crash Stop #1 – October 8, 2003

Please refer to Figure 2. This crash stop was done on moderately ball mill limiting ore that typically averaged 460 dry tph. The picture does suggest some slurry pooling as well as some packing between lifters. The measured mill filling was 25% with a 10% ball load. The lifters also showed some peening due to ball overthrow beyond the charge toe onto the unprotected shell lifters. This crash stop was interesting, but not the "smoking gun" we were looking for.

Figure 2: SAG Mill Crash Stop on 10/8/2003

Crash Stop #2 – March 3, 2004

Please refer to Figures 3-5. This crash stop was done on severely SAG mill limiting ore that typically averaged 360-390 dry tph. In comparison, the worst case SAG mill limiting ore type throughput is 8,160 dry tons per day (340 dtph). The picture shows extensive lifter packing and slurry pooling. Also clearly visible are extensive lifter peening and cracked/missing lifters.

Figure 3: SAG Mill Limited Ore Lifter Packing on 3/3/2003

Figure 4: Lifter Peening From Ball Charge Overthrow
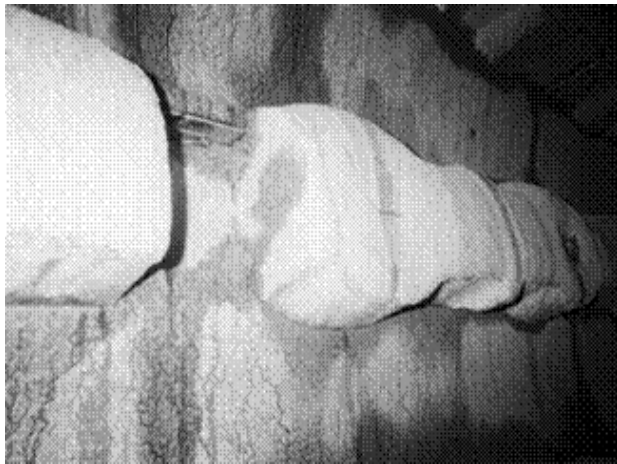
Figure 5: Broken lifters from Charge Overthrow

Crash Stop #3 – June 30, 2004

The reader is asked to refer to Figures 6-7. The purpose of this crash stop was to collect circuit data to aid in the Cortez Hills project's proposed mill expansion feasibility study. A full grind circuit survey, including feed belt cut, crash stop, and grind-out were done to gather all relevant data. The data served to validate parameters used in future computer simulations as well as provide another data point in the DOE project. The moderately SAG mill limiting ore throughput was 420 dtph.

Figure 6: Slurry Pooling with SAG Mill Limited Ore on 6/30/04

Figure 7: Slurry Pooling and Lifter Packing with SAG Mill Limited Ore on 6/30/04

Initial Review of Crash Stop Results

It is very obvious that the crash stops point out many things:
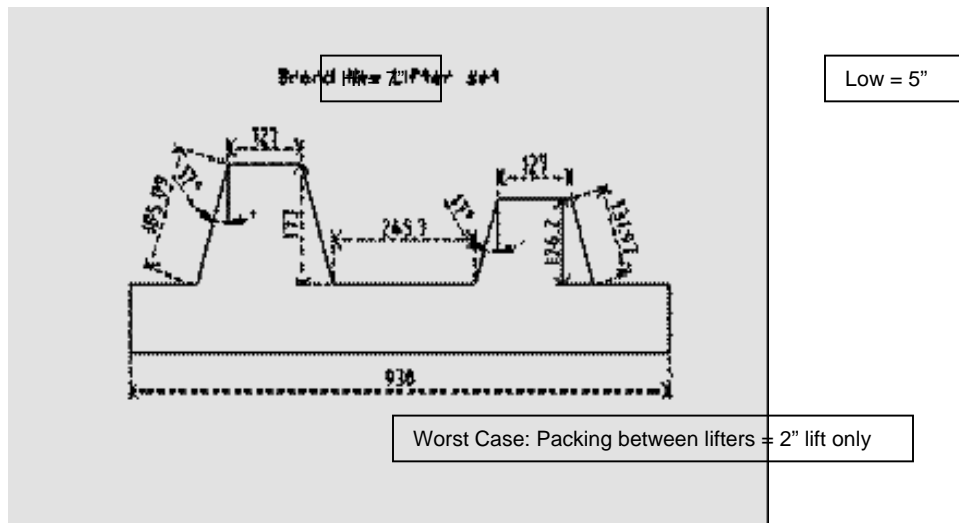
The lifter spacing is too close such that they pack with ore and the effective lift and mill volume is reduced. This would suggest that less of the available mill power can be used for grinding. The lifter face angle is too steep such that high mill speeds required for harder ore result in balls overthrowing the toe of the charge and striking the unprotected mill shell liners. This would suggest that a portion of the applied mill power is wasted turning the mill faster to grind the harder ore as well as the subsequent unnecessary and costly liner breakage and mill downtime.

The mill is not adequately discharging the ground slurry and/or returning it back into the mill. This means that the mill volume is taken up by material that is already product sized. The pooling could lower the energy of ball-to-charge impacts and therefore waste a portion of the applied mill power by "grinding water" and/or re-grinding product sized ore.
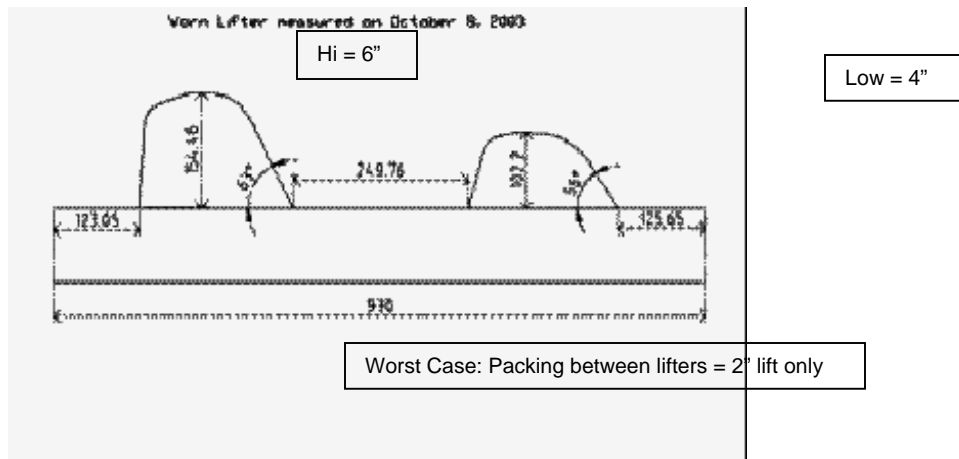
It was then decided to pursue computer simulations of these results as well as solutions to prevent these observations from occurring.

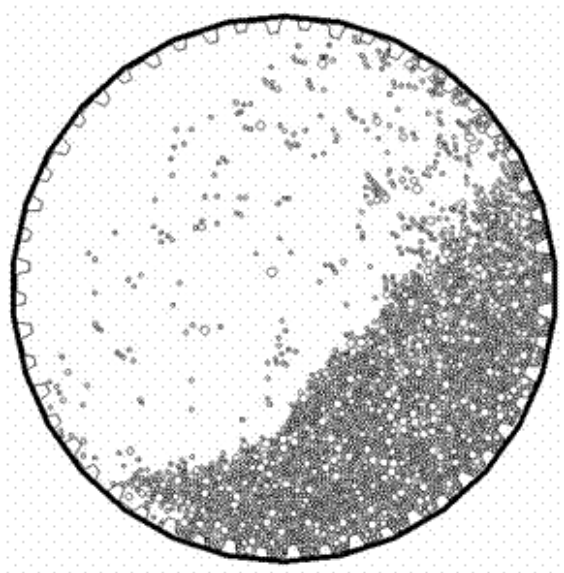**Computer Simulation of Crash Stop Results**

The crash stop measurements, liner profiles, operator observations, and recorded PLC data were then inputted into a drawing software package as well as the MillSoft™ software. The software outputs are depicted in Figures 8-10. The figures illustrate that with packed lifters, the worst case lift is 2" with the concurrent reduction in effective mill diameter of 4". In addition, the MillSoft™ simulation shows that the media hits the unprotected shell with a 17° face angle lifter at mill speeds required to process the harder ore.

Figure 8: New Lifter Set with Packing
(Rajamani and Latchireddi, 2003)

Worn Lifter measured on October 8, 2003

Hi = 6"

Low = 4"

Worst Case: Packing between lifters = 2" lift only

Figure 9: Worn Lifter Set with Packing
**(Rajamani and Latchireddi, 2003)**

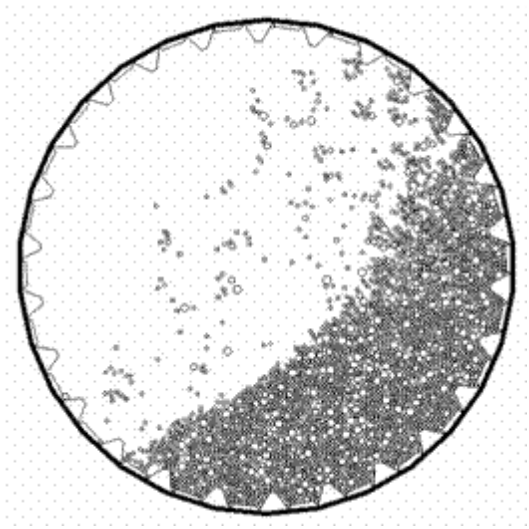**Figure 10: Charge Motion Analysis of 17° Face Angle Lifters**

SHELL LINER DESIGN CHANGE

The above crash stops and subsequent computer modeling told Cortez that we needed to act now before our downtime, mill throughput, and unit energy consumption further deteriorated. We therefore approached the project in these regards. Numerous computer simulations, discussions with local and our sister site Granny Smith and Porgera SAG plants, as well as a thorough literature review drove us to a design eliminating ½ the lifter rows and replacing them with shell plates to minimize the packing and maximize lift and mill volume. In addition, we chose to optimize the lifter face angle for optimum ball trajectory at high mill speeds as well as increase the lifter height for wear life. Metallurgists familiar with SAG plants will know that these types
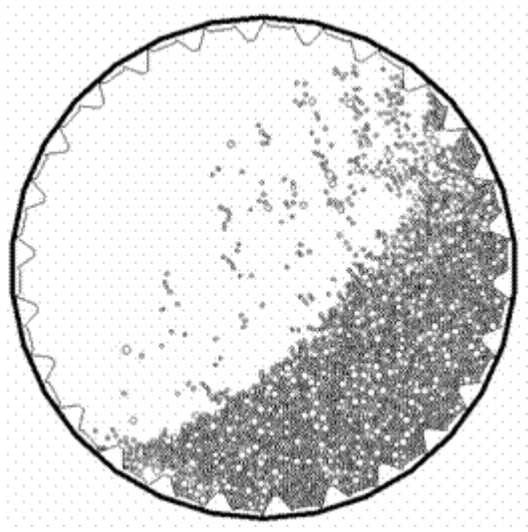
of changes and subsequent operating successes have been numerously documented elsewhere so the writer will not discuss the theory here. Figures 11-13 show the computer simulation trials at 28°, 32°, and 35° face angles, respectively.
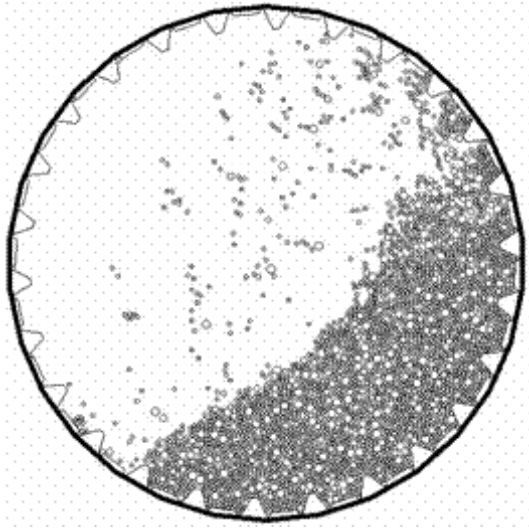
Figure 11: Charge Motion Analysis of 28° Face Angle Lifters
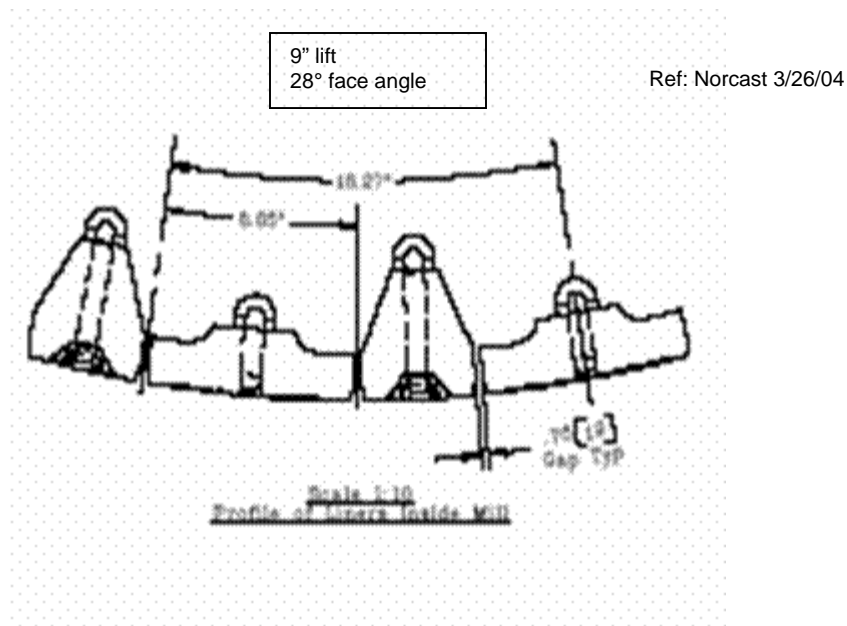

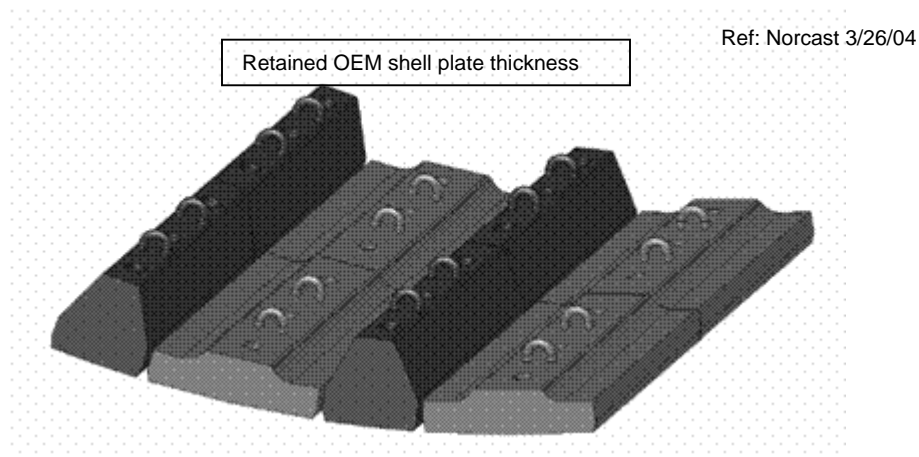**Figure 12: Charge Motion Analysis of 32° Face Angle Lifters**

Figure 13: Charge Motion Analysis of 35° Face Angle Lifters

The 32° lifter was the starting point of optimized ball strikes at high mill speeds. In the end, however, we decided to be conservative, to try to maximize wear life, and settled on a 28° face angle lifter with the belief that a 28° lifter will quickly wear to a 32° lifter. Lift height was also set at 9" above the 4" shell plate. Figures 14-15 shows the final design settled upon.

It is also important to note that we did investigate the "polymet" style shell liner design, but decided against it. It was felt that the rubber would flex and take away from the impact energy – energy that we were trying hard to focus on doing useful work. Further, our research indicated that for high throughput plants with aggressive ore that cast liners were the preferred option for wear and performance.

9" lift
28° face angle

Ref: Norcast 3/26/04

Figure 14: Revised Shell Liner Design Side Profile

Retained OEM shell plate thickness

Ref: Norcast 3/26/04

Figure 15: Revised Shell Liner Design Isometric View

LINER DESIGN CHANGE CONSIDERATIONS

Concurrent to this major liner design change, there were many questions in the background that needed to be resolved before the design could be implemented.

How would we safely handle the heavier cast liners?

The issue was that while the new design had 33% less pieces, each piece now weighed up to 2.5 times more than the old design. The maximum weight to be encountered was 2,000 lbs. We reviewed our current liner handler and decided to send it back to the manufacturer to get it

upgraded and professionally recertified from 3,000 lbs capacity to 4,000 lbs capacity. In addition, we held numerous pre-installation meetings involving the mill maintenance, operations, safety, and management departments as well as the liner manufacturer to break down the liner change step-by-step to ensure adequate equipment and procedures were available. In addition, local and our sister SAG plants were consulted in regards to their liner change-out practices. With all of the above covered, we felt fairly confident that we would safely handle the upcoming design change.

What would the cast liners do to the workplace noise?

The issue was the cast liners would operate noisier than the old design rubber plate-cast lifter combination. We consulted other plants about this and they all responded that it was a non-issue to them because of already established hearing protection policies and that the sound was not obnoxious provided that the mill was operated properly. We left this issue there, but still conducted before and after noise surveys and found that the noise only increased up to 2%.

What effect would the heavier cast liner weight have on the mill shell and mill motor?

Another issue was that the new shell liner design at 41 extra tons would cause undue stress to our mill shell as well as mill motor. We consulted with our mill designer who confirmed that our mill was designed for considerably more shell weight. Calculations were also done that showed only about 100 extra HP was required to start the mill in order to overcome bearing pressure friction after which the "flywheel effect" soon takes over. After the change we were also pleasantly surprised to find that the mill starts up under a full load noticeably easier than the previous design undoubtedly due to this effect.

Could the existing inching drive handle the increased mill weight?

The issue of an inadequate inching drive stemmed from our ball mill inching drive experience where we found that its performance was severely hindered with a fully charged and/or frozen charge ball mill. We again consulted other SAG plants and discovered that this was also a non-issue in regards to a SAG mill because of the large diameter causing a counterweight effect balanced by charge. They further advised that the mill would be most unbalanced when ½ the liner installation was complete such that jogging the mill into place would be difficult as compared to inching it into place. In the end we found that our SAG inching drive did work hardest at this point, but nowhere near the difficulty the ball mill inching drive had on the ball mill under similar circumstances.

How would our operating practice change with the new liners and how long would the learning curve be?

The concern was that the expensive set of new liners would be damaged upon start-up due to operator unfamiliarity running with new mill speed and bearing pressure targets that would be undefined until we actually started running the mill. The resolution was to discuss these concerns with all the operators beforehand and then practice conservatism on mill speed and

aggressiveness on mill bearing pressure upon new liner commissioning. In addition, the operators were given explicit instructions to run the mill under their control rather than Expert System control to learn the new operating regime.

SHELL LINER DESIGN CHANGE OPERATING RESULTS

We would assume that the new design encountered numerous different ore types over its life similar to the previous design's life such that we could come to some valid conclusions. Without extensive work index and mineralogy data, the derived conclusions focus on what the operating data clearly tells us:

Similar mill throughput. Before the change we averaged 411 dtph and after the change we averaged 419 dtph on the first shell liner set. On the second shell liner set we averaged 400 dtph. Essentially the throughput has been similar due to our ore variability.
Overall reduced unit energy consumption on both mills. On average the plant operating work index decreased by 1.2 kWh/ton milled over 2 sets of the new shell liner design. The SAG power draw has been reduced 94-262 kW (126-351 HP) with the new shell liner design. This was due to the SAG grinding more efficiently with optimized ball strikes and feeding a better product to the ball mill circuit, while yielding essentially the same average throughput before and after the design change.
Increased use of the mill volume for grinding. Lifter packing throughout the new shell liner design life has disappeared thereby allowing the use of the entire mill diameter for grinding. Slurry pooling, however, has not been eliminated. Please refer to Figure 16.
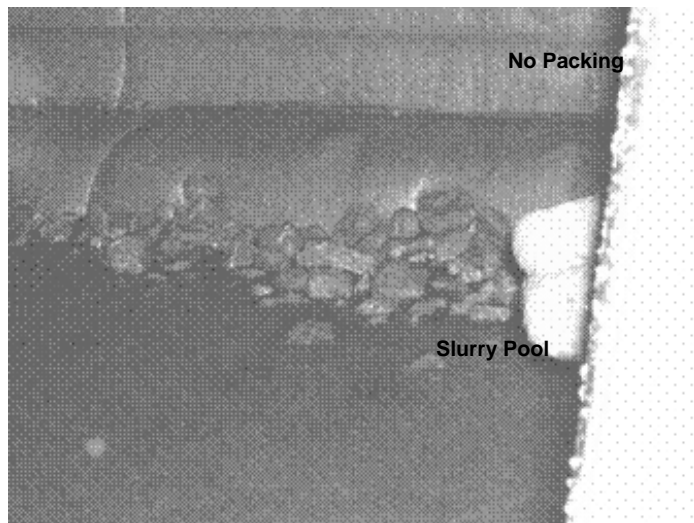
Figure 16: No Lifter Packing with New Shell Liner Design

Virtually eliminated downtime from broken shell liner bolts for the first time in Mill #2 history. Since the new design install we have had no downtime due to shell liner bolt problems.
Increased grinding of critical size material in the SAG. Our SAG now began to perform like a secondary crusher and grinding mill like a SAG mill was conceptually intended to do from its

early beginnings. We started the new design on essentially the same ore type as the old design and immediately noticed less pebbles being recycled to the pebble crusher, but the cyclone feed circuit recirculating load increased with a slight decrease in grinding circuit product size that was still within metallurgical guidelines. This suggested more grinding of critical sized SAG material with the subsequent increase in particle size of typical ball mill feed.

Increased liner life. Measurements and calculations done on both old and new liner designs reveal that the liner wear life has improved 47% to 57 kgs/day steel loss from the previous design's 84 kgs/day (Rajamani and Latchireddi, 2005).

EXPOSING THE INEFFICIENT SAG PULP DISCHARGER

At the same time the new shell design was commissioned Cortez Gold Mine announced its major Cortez Hills gold discovery. A feasibility study team was soon assembled to investigate various process options to handle the Cortez Hills ore. The front runners were keeping the current mill flowsheet versus expanding the mill capacity by 50% to nominal 15,000 stpd. In the early stages of the study it became apparent from operator, peer reviewer, and metallurgical concerns that the SAG would not be able to handle 15,000 stpd fresh feed let alone the +17,000 stpd operating days that would need to occur to make up the nominal 15,000 stpd requirement.

In parallel to the above, the new liner design emphasized the now increased importance of the pebble cone crusher in the SAG circuit compared to the old design to cause the efficient size reduction of critical size material. Whenever the pebble crusher was bypassed for cleaning or maintenance, we noticed an immediate drop in mill throughput on the order of 50-100 stph. Previous to the design change the pebble crusher had at most a 25 stph effect on mill throughput and often sat idle over all ore types. The initial thought was that when the pebble crusher was online, the SAG mill was very efficient in grinding the critical size material in the mill due to the crushed pebbles being discharged from the mill on their next pass through it. When the pebble crusher was bypassed, the effect was almost an immediate 80-100 tph increase of critical size material back into the mill thereby overloading it. This is what was partially occurring, but with the aid of our consultants we soon found that it was primarily due to the inherent weakness of the SAG pulp discharger design.

Imagine the SAG Mill as a Pump

Initially, conventional wisdom told us to think of the SAG mill as just another grinding mill in which ball charge, mill filling, and mill speed were maximized to ensure maximum throughput. Liner design for the SAG was also approached more from a wear perspective rather than a metallurgical and hydraulic-flow perspective. Our University of Utah partners immediately encouraged us to think of the SAG as more of a pump in which the grates and pulp discharger end ("impeller") were designed to allow for optimizing slurry density, mill speed, and mill filling ensuring maximum slurry discharge out of the mill with minimal recirculation of product sized material.

The theoretical maximum SAG discharge is dictated by a "grate-only" (GO) configuration in which the mill is open on the discharge end with no trunnion. The end is covered with grates

without lifters. The maximum flow then becomes a fluid dynamics problem in which head pressure on the inside grates dictate flow. The actual maximum SAG discharge is dictated by the current SAG configuration, which is a radial pulp lifter (RPL) design in our case. The comparison between actual and theoretical gives the pulp removal efficiency so therefore the maximum efficiency is realized by making the current design as close as possible to GO. Please refer to Figure 17.
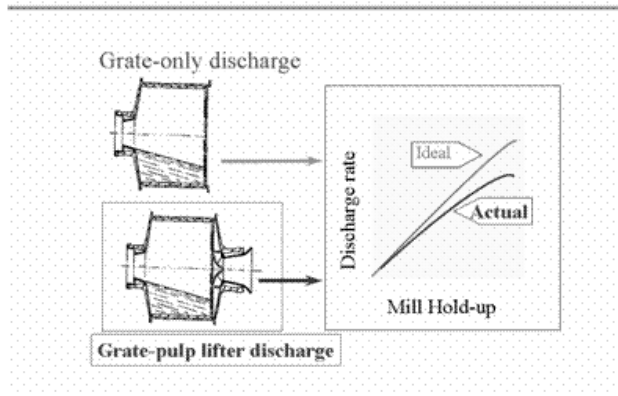
Figure 17: Theoretical Maximum SAG Mill Pulp Discharge Rate (Latchireddi and Rajamani, 2005)

Pulp Flow Modeling

Our University of Utah partners then conducted computer modeling of our pulp discharger using their powerful FlowMod™ software using our 6/30/04 survey data. After several iterations we were left with the results in Table 1. The results clearly show that at best 12,100 stpd would be realized out of our SAG with the current "420 tph ore" and therefore we will fall short of the nominal 15,000 stpd goal.

Table 1: Results of FlowMod™ Simulations on 6/30/04 Ore

Base Case 6/30/04 Survey @ 95% Availability @ Pebble Crusher Feed = 21% of Fresh					
	Fresh Feed		Pebble Crusher	Total SAG Feed	
	dstph	dtpd	dstph	dstph	m3/h
Actual w/ Radial Pulp Lifter	420	9,576	88	508	383
Theoretical Grate Only Discharge	530	12,084	111	641	482
Pulp Removal Efficiency %					79%
Max Incremental Gain	110	2,508	23	133	

Critical Size Material Flow

Using crash stop measurements as well as ore characteristic and mass flow measurements our University of Utah partners were also able to illustrate what was happening with our critical size (pebble) material with the RPL design.

Essentially the critical size material was building up in our SAG mill because as the mill was run faster to grind the harder ore the RPL pulp discharger design would allow for material to come back into the mill after going through the grates (Figure 18). For example, this observation was also documented with pictures from the Cadia Hill mine (Figure 19 - Hart et al., 2001).
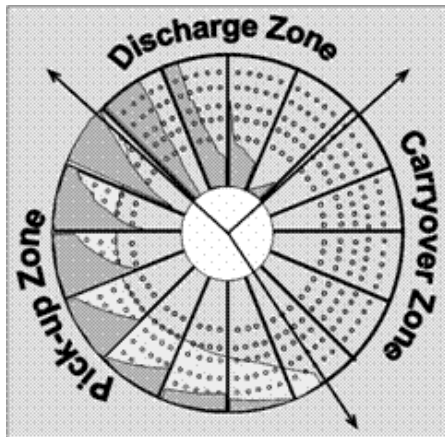

Figure 18: Pulp Discharge Profile with Radial Pulp Lifters (Latchireddi and Rajamani, 2005)


Figure 19: Pebble Flowback at the Cadia Hill SAG Mill (Hart et al., 2001)

As the mill turns faster the critical size material then builds up even more on the interior mill circumference. Our grate design in turn was not optimized with holes towards the outer circumference of the grate since the OEM rubber discharger design prevented this. As much as 12 inches of the outer mill radius was not used for pebble and pulp discharge (Figure 20).
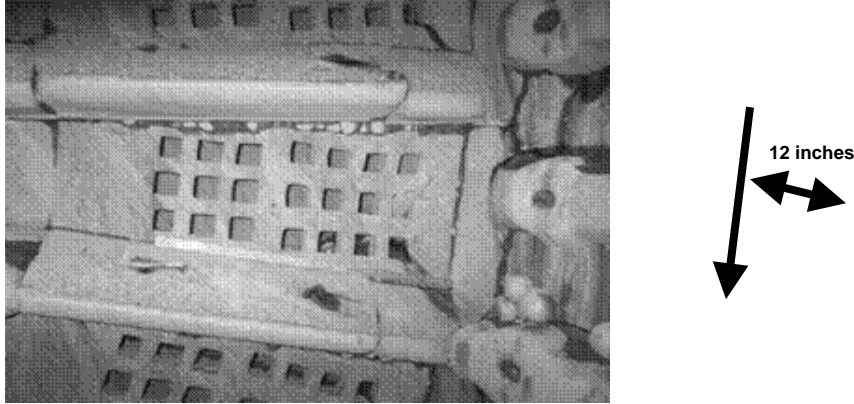
Figure 20: Unavailable Mill Diameter for Pulp and Pebble Discharge at Cortez

Eventually the critical size material and slurry flow-back as well as subsequent slurry pooling built up so much, but not to the levels of traditional mill overloads, such that the mill power decreased due to ball-on-slurry instead of ball-on-rock impacts (Figure 21).


Adverse effect of slurry pooling on grinding process in SAG mill.
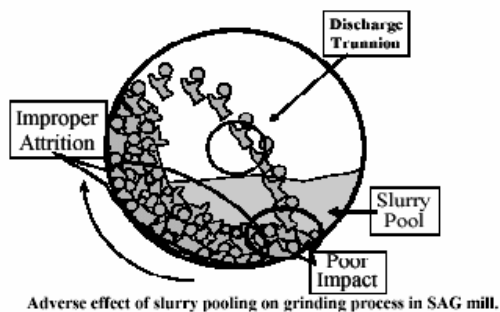
Figure 21: Impact of Slurry Pooling on Grinding Efficiency
(Rajamani and Latchireddi, 2004)

This critical size material overload was further compounded when the pebble crusher was bypassed such that the power draw decrease and load increase happened quicker - often within 5 minutes. The only remedy was to cut throughput by as much as 100-150 tph (Figure 22). The subsequent drawback in addition to throughput reductions is cycling introduced to the downstream mill circuits (Figure 23).
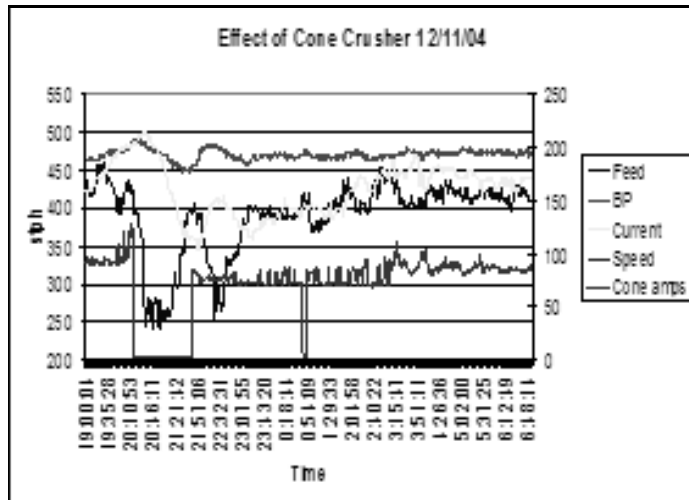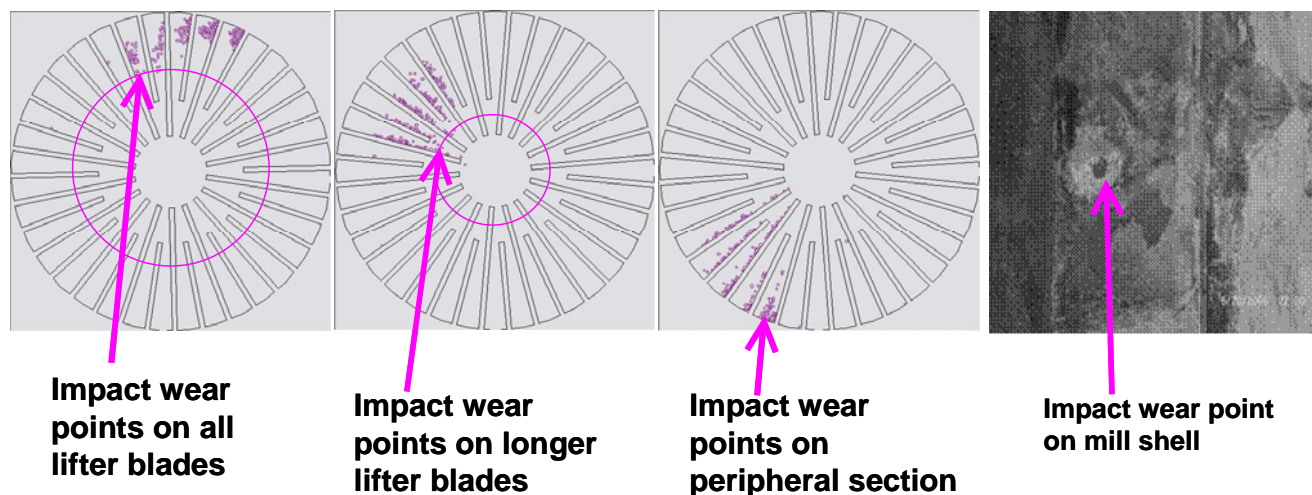
Figure 22: Effect of Pebble Crusher Bypass on Cortez SAG Performance
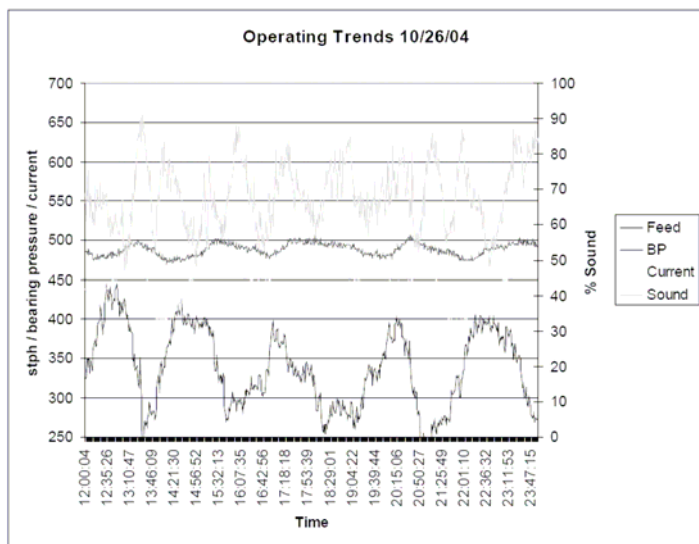
Figure 23: Cortez SAG Circuit Cycling Induced by Pebble Flowback

The critical size recirculation calculated at 31% also explained the impact wear observed on the non-lifting side of the pulp lifter as well as on the rubber filler rings on the periphery of the mill discharge end. Minor impact wear on the Cortez SAG shell due to pebble flow-back is shown in Figure 24.

Impact wear points on all lifter blades

Impact wear points on longer lifter blades

Impact wear points on peripheral section

Impact wear point on mill shell

Figure 24: FlowMod™ Predicted RPL Wear Points (Latchireddi and Rajamani, 2005) Minor Impact Wear on Cortez SAG Shell from Pebble Flow-back

Optimized SAG Discharge End Design

The goal of the next design phase was to address our pulp lifters, pulp discharger, and grate open area orientation for optimum efficiency and flow. With the aforementioned knowledge we decided to pursue with Latchireddi's 2nd generation of pulp lifters called Turbo Pulp Lifters (TPL™), developed specifically for AG/SAG mills with pebble circuits for efficient mill discharge (Latchireddi, 2005).   The theory behind and successes of Latchireddi's first version called the TCPL design (Latchireddi and Morrell, 1997) are well documented (Nicoli et al., 2001).

The next steps were then the engineering design in conjunction with the preparation of an internal AFE to document the project's progress. Through discussions with our Alcoa contacts as well as thorough trending and understanding of the SAG mill dynamics during difficult ore conditions, the AFE justification was based on 3-months payback with the conservative assumptions of:

Minimum throughput gains on the order of 1% on the hard, blocky ores.
A concurrent reduction in unit grinding circuit energy consumption of 0.1 kWh/ton due to reduced regrinding of product sized ore.
Less throughput sensitivity and cycling whenever the pebble crusher is bypassed for operational maintenance. At least 50% (50 tph) of the cycling should be eliminated over every 1.5 hour period per operating day based on analysis of current mill trends.
Increasing the shutdown interval between a complete discharge end liner changes by 1 year to every 4-5 years, as well as allowing for more even discharge end liner wear to correspond with other liner jobs.

Not assumed was the possibility of less throughput sensitivity and cycling whenever the mill coarse ore feed stockpile was low and/or being pushed, such as when the primary crusher was

down for maintenance (12 hours minimum scheduled every 2 weeks). This typically resulted in a feed rate reduction by as much as 100 tph due to the feeding of harder, blocky coarse ore pushed into the apron feeders from the stockpile perimeter.

The design phase progressed relatively smoothly through the last half of 2005 with approved drawings of the Turbo Pulp Lifter (TPL™) issued for casting in early January 2006, at the same time the AFE was approved by Cortez management.

INSTALLATION OF THE TURBO PULP LIFTER

The target date for the TPL™ installation was mid-June 2006 when a one week major mill maintenance shutdown was planned. In the meantime, the same safety discussions mentioned earlier in this paper that took place prior to the installation of the cast shell lifters and plates were reviewed. The TPL™ castings arrived on-site late May 2006 and were then assembled on the ground for maintenance and operations personnel to visualize its installation and operation. This step proved to be the most crucial as, "seeing is truly believing" and enabled everyone to have 100% complete buy-in to this project.

The overall TPL™ installation took about 4.5 days. This included 12 hours for drilling the SAG discharge head for 16 holes to complete the bolt circle pattern, where there were previously tapped holes. No TPL™ liners were installed during the drilling in order to maintain precise drilling conditions. Please refer to Figures 25-27 for snapshots of the TPL™ installation.

Figure 25: TPL™ Laid Out on Ground for Pre-Installation Review

Figure 26: TPL™ Grates on Left. OEM Grates on Right

Figure 27: Drilling SAG Discharge Head to Complete Bolt Circle Pattern

Initial Mill Start-up on the TPL™ Design

After the TPL™ installation we started milling the same ore that we processed immediately prior to the shutdown. This ore was also the most troublesome due to its hard, blocky nature that was compounded by being pushed into the feeders due to a primary crusher shutdown that ultimately induced circuit cycling with the old SAG discharge end design. We immediately noticed with similar before and after mill ball charge levels as well as with operators not yet familiar with the new TPL™ design:

22% increase in throughput rate from 344 wstph to 421 wstph
35% decrease in the SAG mill power draw from 3,908 HP to 2,526 HP (2,915 kW to 1,884 kW). This equates to a 47% decrease in SAG unit energy consumption from 8.98 kWh/ton to 4.74 kWh/ton.
11% decrease in SAG mill speed (11.5 rpm to 10.3 rpm) indicating optimized ball strikes with the concurrent observation of reduced large ball chip scrap generation.
50% increase in pebble discharge rate

7% decrease in ball mill power draw from 4,843 HP to 4,491 HP (3,613 kW to 3,350 kW). This equates to a 24% decrease in ball mill unit energy consumption from 11.13 kWh/ton to 8.43 kWh/ton.

Ball mill circuit load increased due to the higher throughput with the concurrent decrease in grind size from 78% - 200 mesh to 69% - 200 mesh. This is still well within our operating grind target of >62% - 200 mesh. Note that historically our ball mill power draw drops as the mill starts to work from the increase in circulating load.

Assuming a similar ore type over a 30 day month with current electrical costs, operating performance, and mill run-time, we can calculate improvements on a monthly basis of:

742,320 kWh or $67,000 SAG mill electrical savings
181,786 kWh or $17,100 ball mill electrical savings
77 stph or 4,000 ozs of incremental gold production. This translates to $2.4M incremental revenue increase per month at $600 gold.

Operating with the TPL™ Design

For the following discussion the reader is asked to refer to Figures 28-32. As of writing this paper, we now have almost 90 days of experience with running the TPL™ design. Our ore has clearly changed somewhat to a softer ore with more clay, but it is still blocky. Despite this, we are still realizing considerable power savings as compared to historical data on similar high throughput ore. Despite having minimal detailed pre-TPL™ operational data on this ore type with confidence, we can still say that the throughput enhancements exist, but the magnitude is unknown. This is due to the following:

Our pre-TPL™ high throughput ore was all clay with low amounts of rock, whereas the current ore has significantly more rocks. In fact, in July 2006 we established an all-time throughput record for the SAG mill at 522 dry tons per hour, which was only limited by the tailings pumping capacity. The previous throughput record was 514 dtph in February 2003.

We can now process nominal 440-450 dtph throughput rates while the coarse ore stockpile is at low levels and/or is being pushed into the feeders. Prior to the TPL™ installation we were at best 380 tph due to the all coarse and rocky material being pushed in from the pile outskirts.

We can now process nominal 420 dtph whenever the pebble crusher feed magnet is down for repairs hence requiring the pebble crusher to be bypassed. Previous to the TPL™ installation we only managed 330-350 dtph under similar conditions.

Daily comments received from the operators are typical of, "we could never run steady and with confidence like this before with the old design for fear of the SAG mill getting quickly out of control."

Aside from the above improvements we have noticed:

Significantly steadier mill trends as opposed to the previous cyclical trends. The operators can now make their small changes in a steady manner without worrying about quick negative circuit responses, whereas big step changes had to be done previous to the TPL™ installation.

The TPL™ resulted in a 3.1 kWh/ton milled reduction in plant operating work index compared to the OEM pulp discharger combined with the new shell liner design (Figure 28).

The plant operating work index has decreased by a nominal 3.6 kWh/ton compared to the OEM shell liner and OEM pulp discharger design (Figure 28).

While the SAG unit power consumption has decreased, some of the required breakage energy has to be absorbed somewhere to comply with the laws of physics. In our case we have seen evidence of this in the pebble crusher circuit. The pebble crusher current draw has increased by about 10 amps with about a 20 tph increase in pebble discharge rate. This translates to about 0.4 kWh/ton increase in pebble crusher work input, which is still markedly less than the SAG mill unit power consumption decrease. This would further reinforce previous beliefs that ore over-grinding due to recirculation back into the SAG was occurring before the design change.

There is a greater emphasis on the pebble crusher to maximize mill throughput due to the increased rate and particle size of pebble discharge from the SAG. The crusher circuit has to be used efficiently to enable the pebbles to pass into the ball mill circuit after the second trip through the SAG mill.

The renewed importance of prudent and careful utilization of SAG speeds to maximize mill production. Increase speeds too quickly and the mill quickly empties and/or overloads the pebble crusher thereby requiring it to be bypassed. This in turn re-introduces coarse size material to the SAG. In turn, the material that had a difficult time being ground the first time through, passes through the mill again with the concurrent waste in applied energy. For example, now a 0.1 rpm change in SAG speed equates to a 20 tph change in pebble discharge rate. Prior to the TPL™, we required a 1.0 rpm change to get the same result.

Steadier SAG ball consumption rates due to the optimized ball strikes and slower mill speed. We are expecting liner life to also increase as a result of the slower mill speeds (Figure 30).

Grinding circuit P80 stabilized after the TPL™ installation (Figure 31). We suspect this is due to a more consistently sized product from the SAG mill circuit due to the TPL™ installation.

Ball mill power draw appears more stable after the TPL™ installation (Figure 32). We also suspect this is due to a more consistently sized product from the SAG mill circuit due to the TPL™ installation.
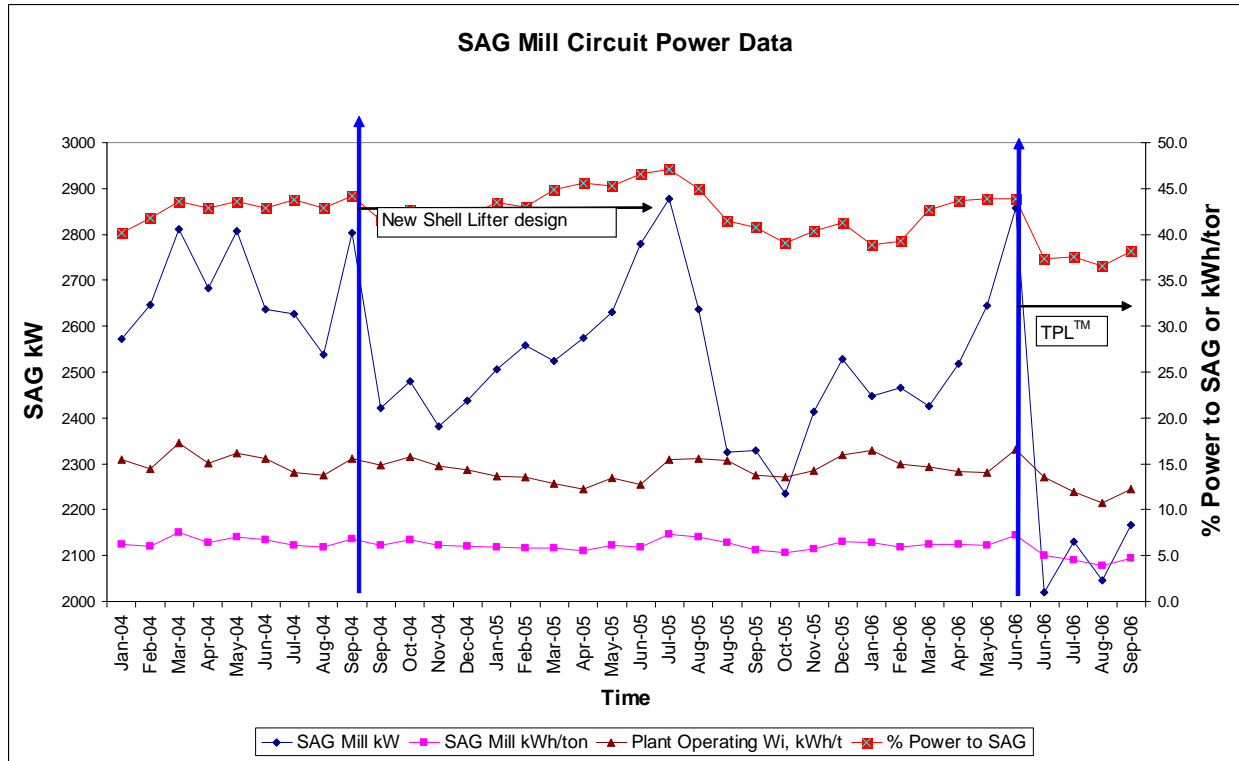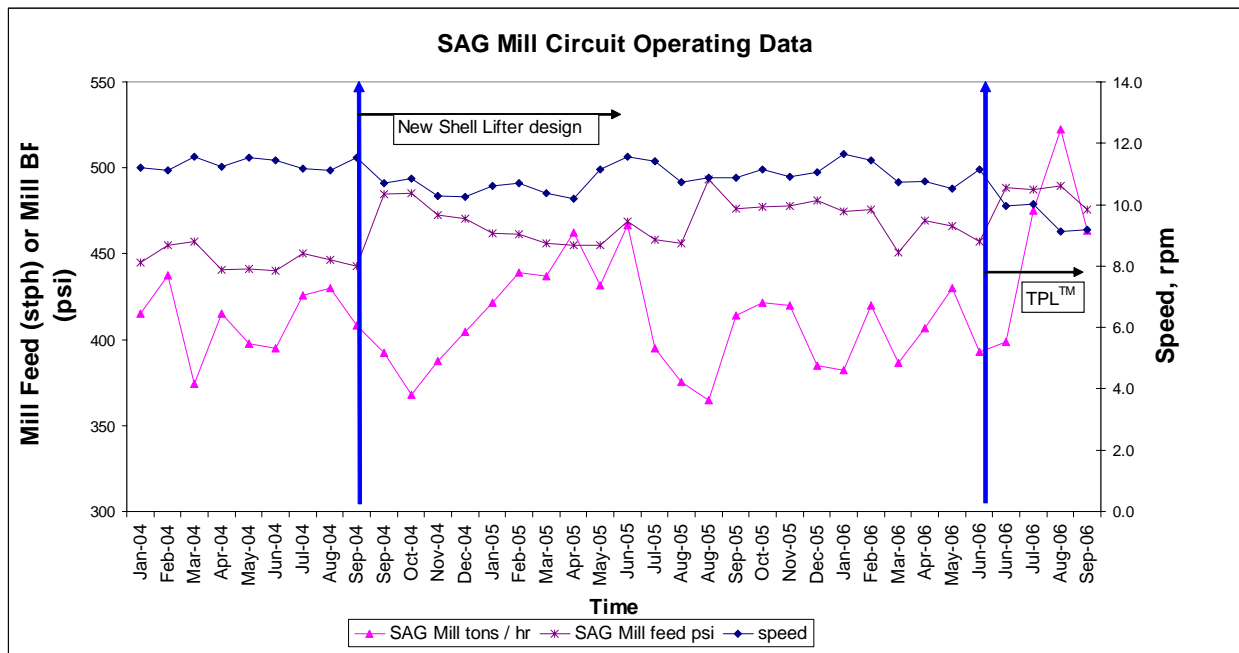
Figure 28: SAG Mill Circuit Power Trend
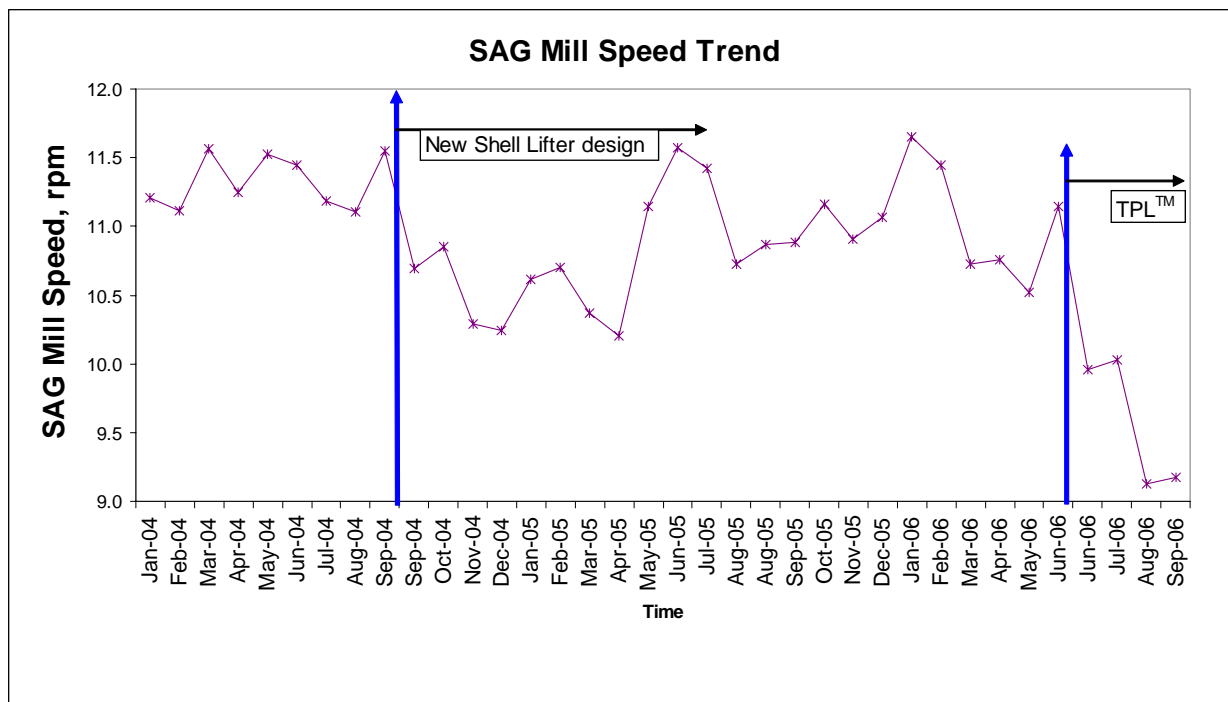

Figure 29: SAG Mill Circuit Operating Trend

Figure 30: SAG Mill Circuit Speed Trend
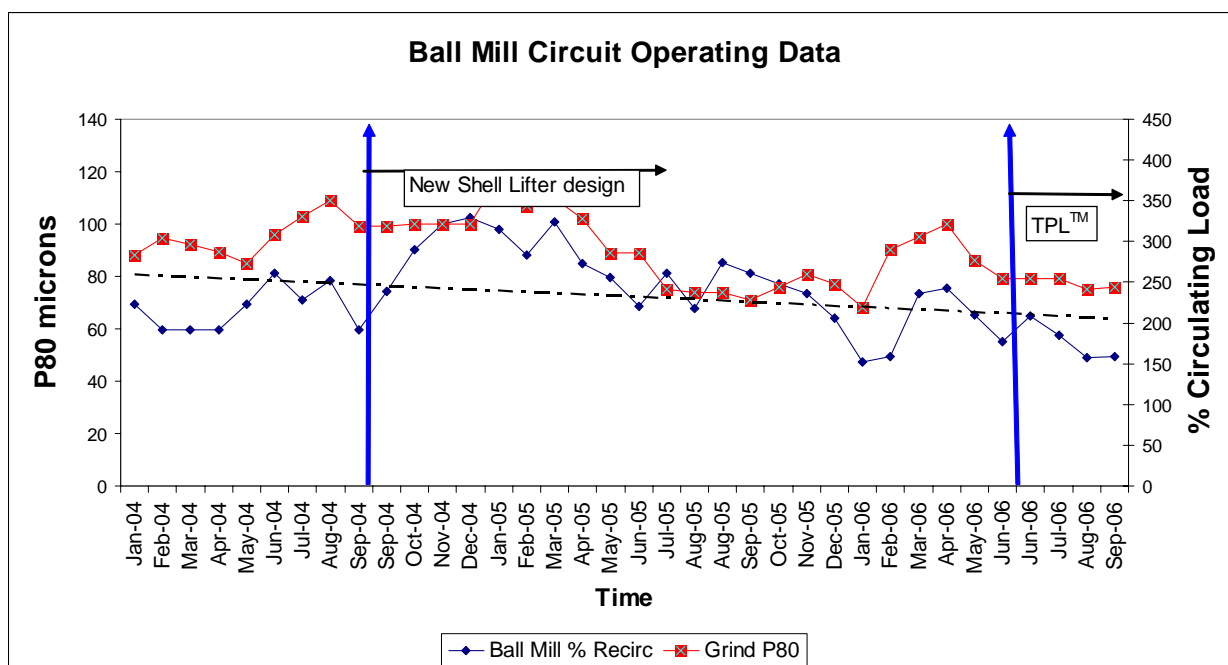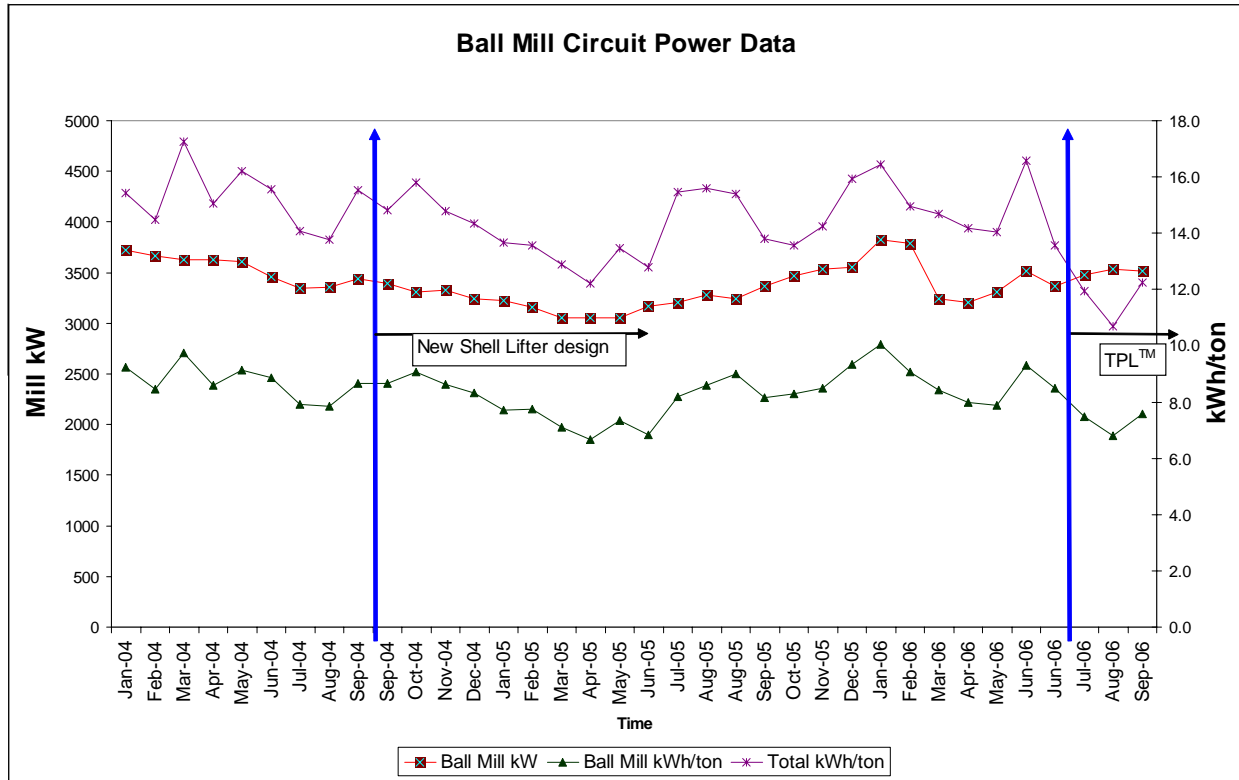

Figure 31: Ball Mill Circuit P80 Trend

Figure 32: Ball Mill Circuit Power Trend

CONCLUSION

We are now very pleased with the SAG mill performance. All expectations were surpassed and as of now the plant bottlenecks have shifted towards the downstream CCD thickeners, cyanide destruction circuit, and tailings unit operations. The next step is to optimize the particle size to the pebble crusher so as to not to overload it. With the new design we switched to slots from square holes, while retaining the same minimum hole dimension of 2.75 inches. This was to provide similar before and after comparisons of the RPL to TPL™ designs. We are now finding that with the new discharge end design, pebble discharge rate can overwhelm the pebble crusher such that it has to be repeatedly bypassed if the operators are not careful in balancing the mill speed to the CSS of the pebble crusher. Further, as the grates wear the pebble throughput will only increase and could ultimately hinder plant throughput. As such, we will be modeling different grate slot configurations and dimensions to balance the pebble throughput against the SAG grinding power that is still available for grinding.

ACKNOWLEDGEMENTS

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