Optimization of the Design of SAG Mill Internals Using High Fidelity Simulation

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September, 2001

ABSTRACT

High Fidelity Simulation of SAG milling is a technique, which uses DEM, CFD and FEM to create realistic Multiphysics models to describe the motion of balls, rocks and slurry and attendant breakage of particles as they are influenced by moving liner/lifters and grates.

This paper presents the application of high fidelity 3D simulation techniques to the optimization of SAG mill performance through

1. Changes in liner/lifter design to maximize throughput while maintaining acceptable wear levels.
2. Changes in ball size to maximize particle breakage without producing exceptionally high impact forces.
3. Changes in grate and pan lifter designs to decrease internal mill recycle and increase throughput.

Future possibilities concerning the application of this exciting technology are discussed.

INTRODUCTION

The last decade has seen an exciting new level of process modeling ushered into the mineral industry. High fidelity physics-based modeling tools consisting of discrete element methods (DEM), computational fluid dynamics (CFD) and discrete grain breakage models allow the internal mechanics of SAG and AG mills to be described with a level of detail previously unrealizable. The DEM simulations used are based on the application of Newton's 2nd Law of Motion to all discrete elements in the mill (see Figure 1) including balls of varying sizes (spheres) and particles of varying sizes (tetrahedra) as they are effected by other moving elements such as lifters, liners and grates. The post-processing of such simulations allows the calculation of impact and shear forces, impact and shear energy spectra for dissipation into particle classes and maps of energy dissipation along liner/lifter profiles. In turn, these calculations can be used to predict wear on all wear surfaces as well as breakage of particles on a size by size basis and ball/liner breakage

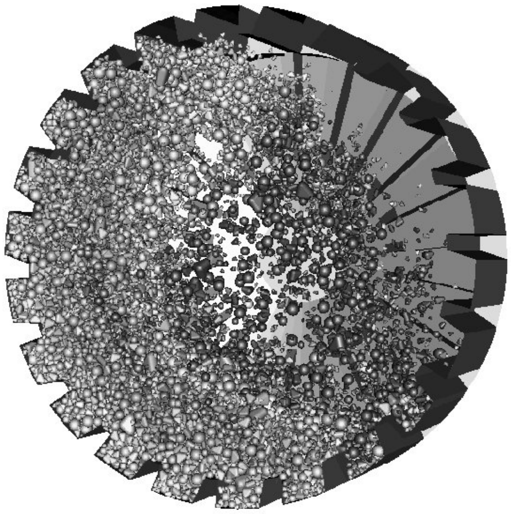


Figure 1. Example of HFS modeling of ball and particle motion in a slice of SAG mill using DEM simulation.

The CFD simulations used are based on the application of the Navier Stokes equation (with boundary turbulence models and free surface algorithms) to fluid flow field behavior over surfaces and around balls and particles. An example of a CFD simulation of slurry combined with a DEM simulation for balls (25 mm top size) in a laboratory ball mill (250 mm) is shown in the snapshot given in Figure 2. The post-processing of these simulations allows slurry profiles and flow to be established in the mill as well as calculation of changes in impact and shear forces and energy dissipation with slurry rheology.

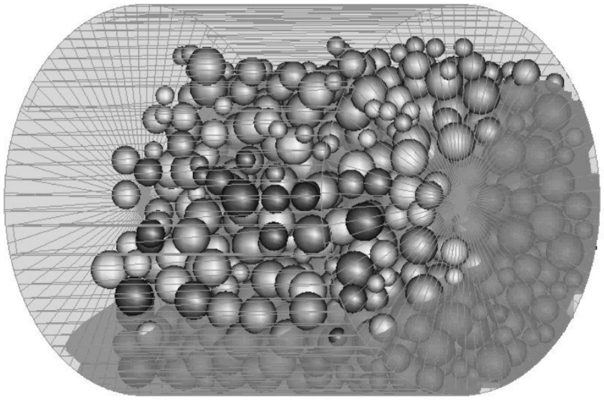


Figure 2. Snapshot of HFS simulation of ball (DEM) and slurry (CFD) motion inside a batch mill.

The breakage simulations involve the application of a crack energy balance (Potapov, 1996). An example of a simulation of single particle breakage involving a 1.7mm particle with a 25mm ball in an ultra fast load cell (Weichert and Herbst, 1983) is shown in Figure 3. Post-processing of the data allows the calculation of energy input as well the progeny size distribution and the kinetic energy associated with the fragments as they leave the breakage zone.

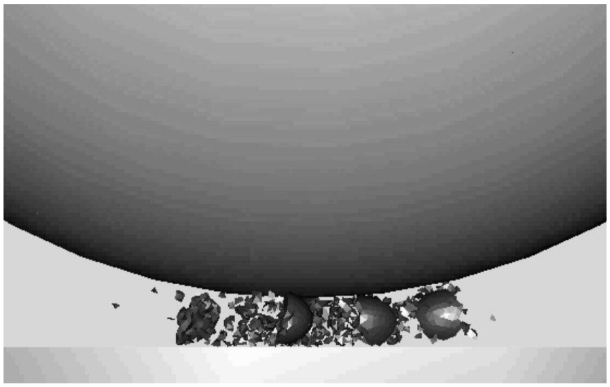
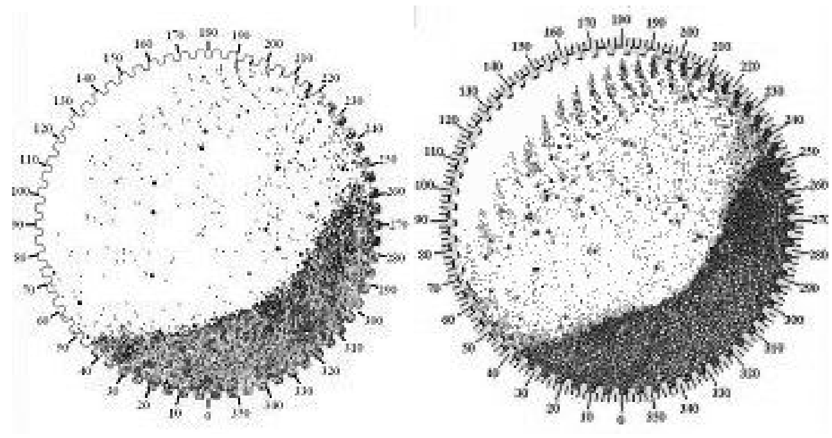


Figure 3. Snapshot of HFS simulation for particle breakage.

Recent developments in High Fidelity Simulation represent the most important advancement in modeling since the introduction of Population Balance Models in the mid nineteen sixties. Further, it is important to realize these simulations are not academic curiosities, they are in fact well documented tools which are being applied in plants today.

As recently as two years ago DEM simulations of SAG mills were normally restricted to 2D (where balls and particles are treated as discs) such as shown in Figure 4a. Some investigators used the 2D simulation to predict trajectories and calculate impact energy frequencies to select liner lifter profiles in the past (Rajamani and Mishra, 1996, Sherman and Rajamani, 1997). More recently the shortcomings of 2D prediction have been exposed and 3D predictions (in which balls and particles are modeled as three dimensional objects) have been found to be quantitatively more accurate (Herbst and Flintoff, 2001). This point is illustrated in Figures 4 & 5 where it can be seen that predictions are somewhat different in the motion and significantly different on a size by size basis for impact energy in 5a but most importantly that the 2D predicted lifter plate profile misses that measured experimentally in 5b while the 3D predictions are in excellent agreement (virtually undistinguishable in the plot) with the measurement.



4a 4b

Figure 4. Comparison of charge motion predicted by 2D and 3D DEM simulations for a Large SAG mill.

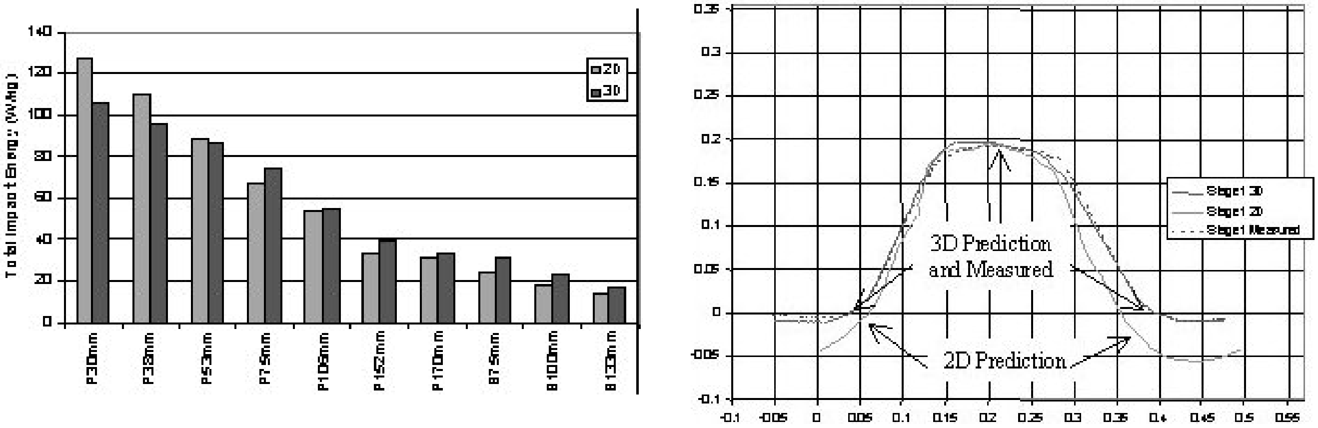


Figure 5. Comparison of quantitative predictions of impact energy dissipation into particles and balls on a size by size basis (above) and wear along a lifter and plate assembly (below) for 2D and 3D simulations

Svedala Optimization Services and Conveyor Dynamics Inc. recently formed an alliance to further develop, validate and use this technology for SAG mill optimization. Three dimensional tools are obviously the most interesting and valuable because of their accuracy. Figure 6 shows a snapshot of a product of the alliance in the form of a simulation of the internal mechanics of a full SAG mill (11.5m x 8.1m) involving over a million elements. It is significant that as recently as January 2001 it was anticipated by many investigators in this field that full mill simulations involving such a large number of particles would not be practical for several years.

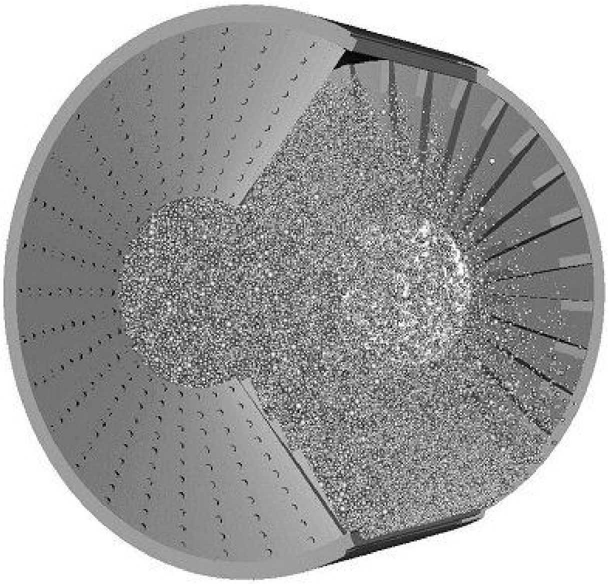


Figure 6. High Fidelity Simulation snapshot of DEM ball and particle motion in an entire SAG mill.

This high fidelity full mill simulation has permitted prediction of 3D motion of balls and particles, mapping of power draw, impact energy dissipation and shear work done by balls and particles on the liners as a function of distance down the mill axis. Figure 7 shows a plot of simulated power draw (per unit length of mill) beginning at the feed end of the mill (slice 1) and proceeding to the discharge end (slice 17). Here we see some interesting and here-to-fore undisclosed behavior resulting from end-effects. The power draw of the feed and discharge cones is very high, while the power in the slices adjacent to the cones (slice 2, 16) are very low and a relatively stable medium magnitude power occurs in the middle of the mill (slices 5-13). Such a profile is consistent with observations of wear in a variety of mills.

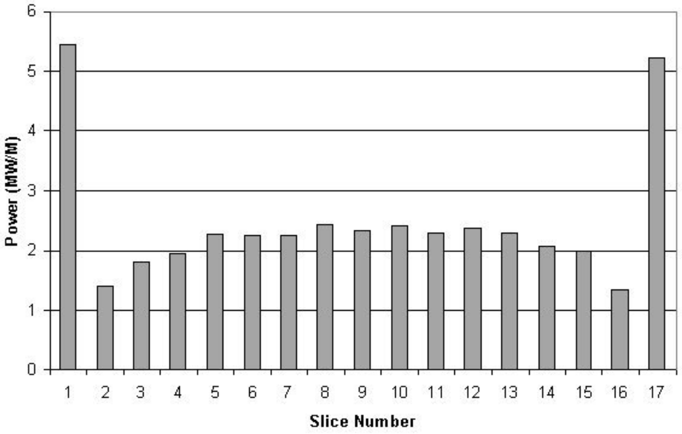


Figure 7. Predicted power as a function of distance down the mill for complete mill simulation.

The information contained in Figure 7 can in turn be used to accurately predict mill power (power predicted and power measured total are 16.9MW and 16.4-17.5MW respectively) and to estimate quite precisely wear rates (Qiu, etal, 2001) and breakage rates (Nordell, et al, 2001) for different internal configurations of liners, lifters and grates as a function of ball size, particle size, media and ore filling and mill speed. Figure 8 shows the associated predictions of shear work (per unit area of liner/lifter) which is linearly related to wear and selection functions which determines breakage rates on a size by size basis.

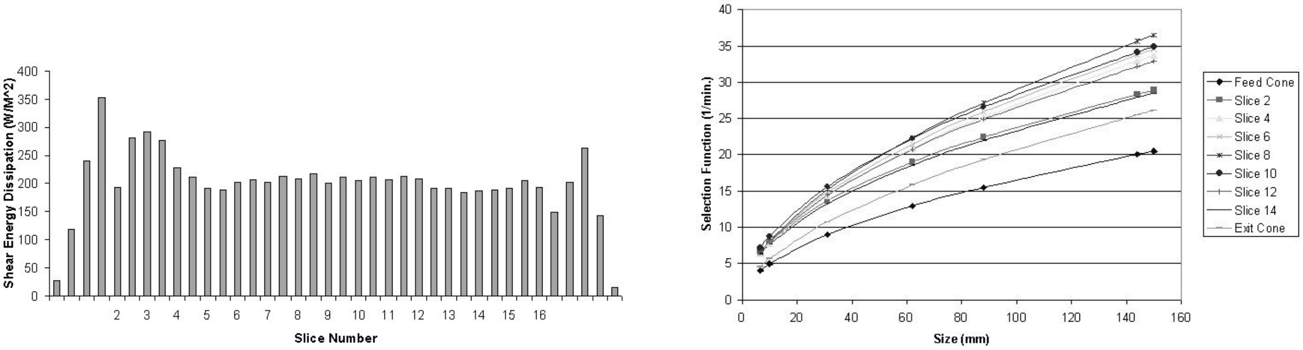


Figure 8. Predicted variations in shear energy dissipation and breakage rates as a function of position from full mill simulation.

It is apparent from the figure that HFS is capable of predicting important spatial details of breakage and wear in a mill. Considering the fact that internals design can have a dramatic influence on mill performance, it is not surprising that engineering rules of thumb for SAG internals selection are giving way to simulation based optimization methodologies.

METHODOLOGIES AND APPLICATIONS

A combination of HFS tools and process experience has lead to a benefit oriented approach to liner lifter design which is based on an analysis of both wear and throughput.

The major steps in the methodology are as follows:

1) Specify Mill Dimensions and Operating Variables
2) Calibrate HFS Models
3) Use Svedala HFS to Optimize Profiles for Target Mill
4) Verify Performance

Step one involves the determination of physical variables (lengths, widths, masses, etc). Step two involves measurement of ore breakage properties and specification of reference liner wear rates. Illustrations of the type of activities that occur during the last two steps are in the three examples below.

Shell Lifter Evaluation

Based on industry experience indicating that more open lifter profiles may be more effective than traditional designs, one mineral producer decided to evaluate charge motion, impact energy dissipation as it relates to breakage and shear work as it relates to lifter liner wear for two profiles as shown in Figure 9.

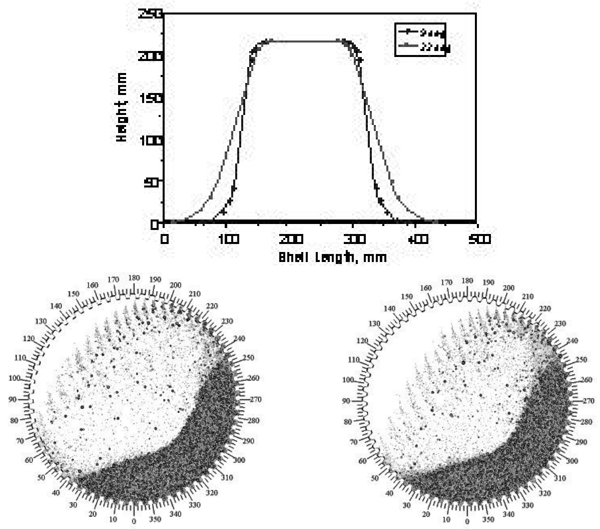


Figure 9. Three Dimensional DEM simulations of charge motion with closed (lower release angle) and open (higher release angle) lifter profiles.

Three-dimensional simulations were performed for each profile over the life of each liner to predict profile evolution and its effect on power draw as shown in Figure 10.

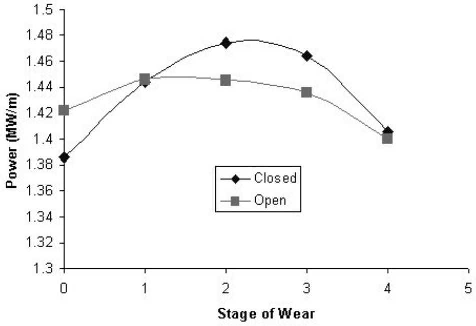


Figure 10. HFS power draw simulation over the lifetime of the two profiles evaluated.

The wear life of each was estimated from the simulation time required to achieve a two-inch lifter height for each. In addition, impact energy spectra were calculated throughout the liner life of each. In turn these simulated impact energy spectra were combined with impact breakage test data to estimate specific selection and breakage functions for each of the profiles at each of four stages in its life as shown in Figure 11.

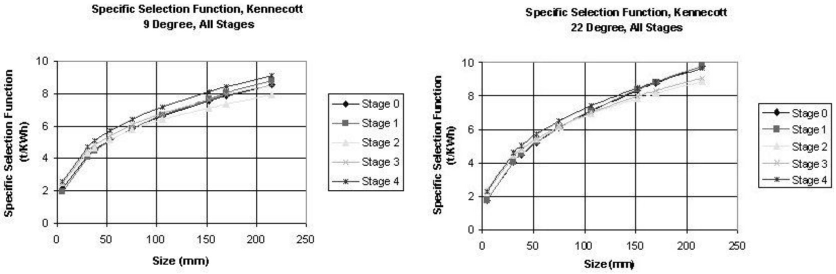


Figure 11. Specific selection functions estimated for open and closed profiles at each stage in the wear process.

Because specific selection functions are energy normalized, differences in these values can be directly attributed to changes in energy efficiency (Herbst and Fuerstenau, 1973) with the highest value for a given size representing the highest efficiency. Thus the different profiles yield different energy efficiencies and the efficiency evolves differently over time for each.

The resulting specific selection functions and power draw characteristics were input to the dynamic flowsheet simulator MinOOcad, to obtain throughput predictions for each profile (Herbst and Pate, 1999).

An analysis of the throughput and wear for the simulations indicate that the more open profile is superior. Plant tests involving the two lifter profiles were performed. The statistical package MILLSTAT (Song, etal, 2001) was used to eliminate the effect of different ore characteristics and operating conditions in this evaluation to produce a true apples to apples comparison. A comparison of the simulated and observed performance is shown in Table 1.

Table 1. Comparison of predicted and measured power and throughput for alternative profiles.

Lifter Configuration	PI Power, MW	DEM Power, MW	Relative PI Throughput	Relative DEM Throughput
Closed	6.33	6.33	100%	100%
Open	6.46	6.46	104.4%	102-104%

It is significant that the predictions are extremely close to the plant determined values.

Ball Size Evaluation

The selection of an optimum top ball size for a large SAG mill is determined by several factors: wear rate, particle breakage effectiveness and liner damage. This example shows how 3D DEM can be used to provide quantitative input on each of these factors. In this case the performance of three different top ball sizes (125, 150 and 175 mm) are evaluated in an otherwise constant environment of ore and ball filling, lifter profile and mill speed. The results of this comparison are shown in Figures 12, 13 and 14.

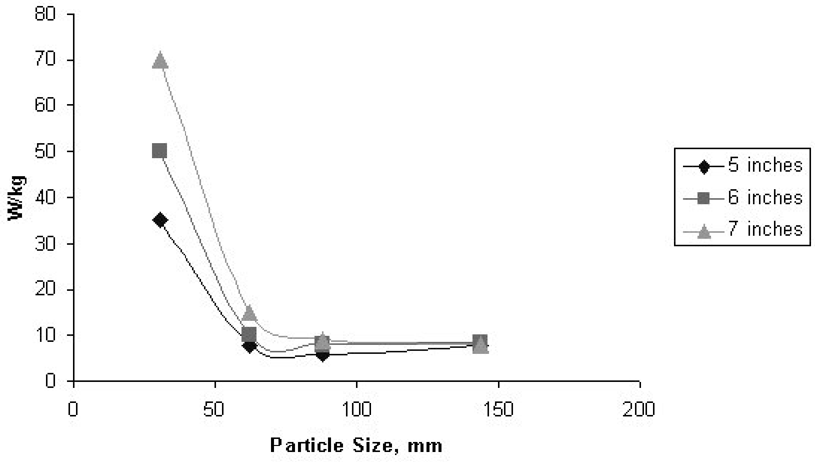


Figure 12. Calculated specific power delivered to various size particles for three top size balls.

Here we see that particles between 60 and 80 mm receive the lowest specific power of all sizes but that the larger balls do increase the absolute amount delivered to these “hard-to-grind” sizes.

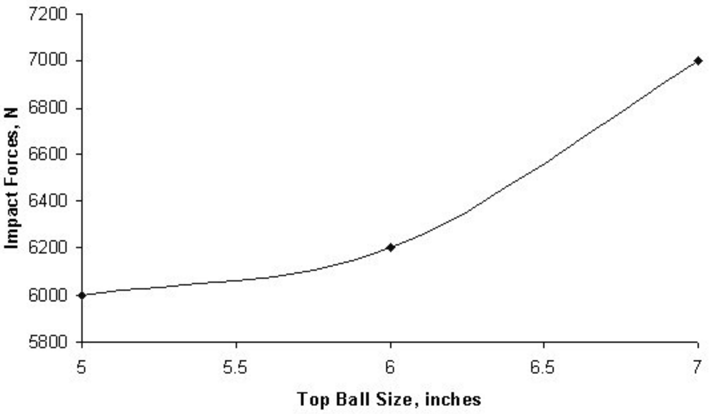


Figure 13. “Maximum” impact force (value at which 80% of the impacts are less forceful) as a function of ball size.

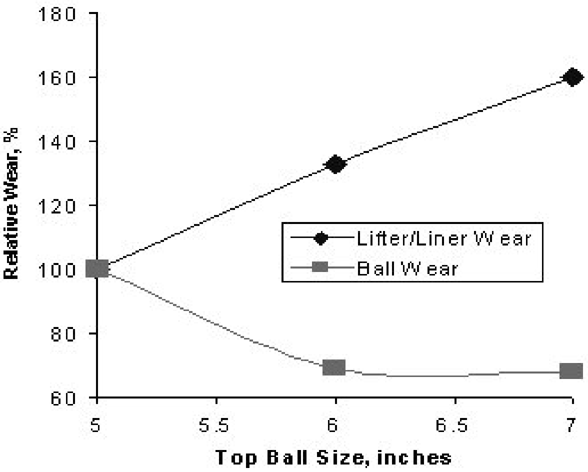


Figure 14. Expected wear on liner/lifters and balls.

In these figures we can see the following trends:

1) As the top ball size is increased the impact energy available to particles for breakage increases with the smallest particles receiving the largest increases.
2) As the top ball size is increased the impact force on the liner increase exponentially increasing the chances of liner breakage.
3) As the top ball size is increased the shear energy dissipated on ball and liner surfaces increases which suggest higher wear (per unit of wear surface).

A final decision about the best top size would involve a weighting of each of the factors in an economic objective function.

Pan Lifters and Grates

In some instances SAG throughput is clearly limited by transport through the backend of the mill. The HFS methodology provides a means of analyzing such situations and evaluate alternatives to remove this type of transport limitation. In this illustration of the use of HFS a 3D model of the mill backend was built as shown in the snapshots in Figure 15.

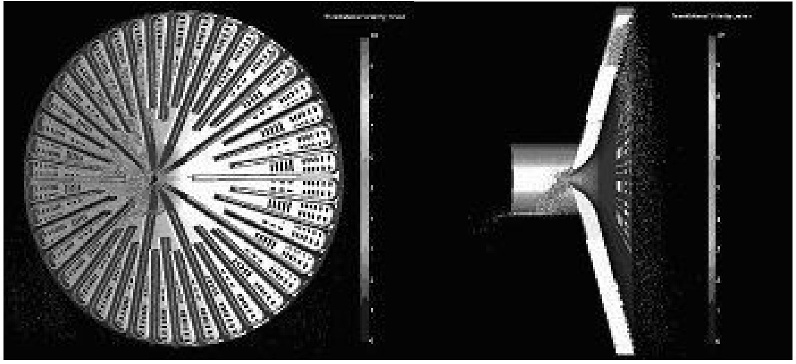


Figure 15. Snapshots of radial pulp lifter and grate simulation.

In the simulation, particles of various sizes are picked up by the radial pan lifters, and a portion of the material picked up is discharged into the center cone, at high speed (low speed) these portions are 30% (50%) while 70% (50%) of the material is recycled back into the mill. An alternative layout of pan lifters and grates was also evaluated in the same way. For this alternate design, 85% (89%) of the material is discharged into the cone while only 15% (11%) is recycled back into the mill. Plant data is being collected to determine whether the performance of the alternative design is consistent with the predictions.

CONCLUSIONS

This paper has presented a methodology developed for optimal design of mill internals. This methodology is based on validated High Fidelity Simulation tools including 3D Discrete Element Modeling, Computational Fluid Dynamics and Discrete Grain Breakage Code. It has been demonstrated that this methodology allows best designs to be identified based on both predicted wear life and mill throughput. Finally, a statistical technique was shown to be very useful in determining whether predicted performance improvements are in fact achieved in the plant.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Drs X. Qiu, A. Potapov, M. Song and W. Pate in running and analyzing the simulations presented here.

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