Mine-to-Mill Optimization of Aggregate Production

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ABSTRACT

Mine-to-Mill optimization is a total systems approach to the reduction of energy and cost in mining and mineral processing operations. Developed at the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Queensland, Australia, the Mine-to-Mill approach attempts to minimize energy consumption through the optimization of all steps in the size reduction process. The approach involves sampling and modeling of blasting and processing, followed by computer simulation to optimize the operation and develop alternatives. The most promising alternatives are implemented, and sampling is conducted to quantify energy savings. In the current project, the primary objective is to adapt the JKMRC Mine-to-Mill technology to the aggregates industry.

The second phase of this project is being carried out at the Pittsboro Quarry located south of Chapel Hill, North Carolina. This quarry is owned by 3M Corporation and operated by Luck Stone. Based on lessons learned from the first phase work, long-term monitoring (~ three months) of all quarry operations is being carried out to minimize the impact of geological changes during the mining process. To date, the blasting and processing operations have been audited and modeled, the long-term monitoring of current Luck Stone practice has been completed, and a modified blasting approach has been implemented based on the results of simulations using JKSimBlast and JKSimPlant. The modified blasting approach is expected to increase the primary throughput by 15% and the secondary throughput by approximately 6%, with an overall specific energy reduction of around 1%. Long-term monitoring is currently underway to evaluate the impact the modified blasting approach. This report summarizes the current status of work at the Pittsboro Quarry.

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EXECUTIVE SUMMARY

Mine-to-Mill optimization is a total systems approach to the reduction of energy and cost in mining and mineral processing operations. Developed at the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Queensland, Australia, the Mine-to-Mill approach attempts to minimize energy consumption through the optimization of all steps in the size reduction process. The approach involves sampling and modeling of blasting and processing, followed by computer simulation to optimize the operation and develop alternatives. The most promising alternatives are implemented, and sampling is conducted to quantify energy savings. In the current research project, the primary objective is to adapt the JKMRC Mine-to-Mill technology to the aggregates industry. The first phase of this project was carried out at the Bealeton Quarry near Fredericksburg, Virginia. The second phase of this project is being carried out at the Pittsboro Quarry south of Chapel Hill, North Carolina. Both quarries are operated by Luck Stone Corporation of Richmond, Virginia.

A typical Mine-to-Mill optimization effort includes four steps: (i) scoping study, (ii) analysis, (iii) optimization, and (iv) implementation. The scoping study consists of a site visit to review current mining and processing practices and discover possible areas for improvement. The analysis step involves a detailed survey of all aspects of a mining operation from blasting to crushing and screening. Rock domains are identified and rock mass characteristics are determined. Samples are collected around all crushers and screens under a variety of operating conditions in order to obtain information for use in the JKSimBlast and JKSimPlant models. The data collected from the analysis step are used in the optimization step in conjunction with the JKSimBlast and JKSimPlant computer packages to optimize the mine and plant operating strategies. Finally, the most promising operating strategies identified from the optimization step are used in the implementation step to improve the total system performance. Once again, a detailed analysis is an integral part of this final step in order to quantify any improvements made in the overall throughput, cost, or energy utilization of the operation. Throughout the Mine-to-Mill process, training and technology transfer are critical in order for benefits to be sustained at the operation being studied, as well as transferred to other operations within the company.

The project entered its second year with a detailed audit of the Pittsboro Quarry in North Carolina, carried out between August 9 and 18, 2005. The Pittsboro audit included one primary, seven secondary and three tertiary plant surveys. Since the quarry supplies material to both the 3M and Luck Stone plants, the audit was extended to include primary and secondary surveys on the 3M material. The sizing and monitoring data were used to develop a comprehensive model of the Pittsboro operation, on both rock sources.

The test blast (8605) on Luck Stone feed was well fragmented, mostly due to the favorable ore hardness and rockmass conditions. The amount of fines was considerably higher than typically seen at the quarry, forcing the throughput to the secondary plant to be limited to avoid overloading of the new Bivitec screen (installed to

reject plastic fines from the crusher run). This unexpected issue necessitated more surveys than planned to adequately quantify the performance envelope of the secondary plant. In comparison, the primary and secondary plant surveys on 3M feed (from a separate blast, 8505) showed considerably coarser product than the Luck Stone test blast.

The blasting and processing plant at Pittsboro has been successfully modeled using JKSimBlast and JKSimPlant simulation packages. The blast model was based on the blast design variables and rock properties. The predicted Run-of-Mine (ROM) fragmentation appears in line with image analysis results obtained in the field. The plant models were based on the detailed analysis of comprehensive plant audit data collected at Pittsboro. These models were used to investigate a range of new blast design recommendations aiming to reduce the amount of +150 mm oversize, while not increasing the percent crusher run (-38 mm) significantly.

On the basis of simulations, there is scope to increase the primary and secondary production rates with a small reduction in the overall energy consumption by changing the blast design according to guidelines drawn up in consultation with Luck Stone. The modified blast designs should increase the primary throughput by 15% and secondary throughput by approximately 6%, with an overall specific energy reduction of around 1%. The resulting base fraction in the ROM is expected to increase by 2% from 36% to 38%. The secondary plant feed size will be finer, resulting in a lower circulating load around the crusher. Though the net yield to the tertiary plant is expected to reduce on account of the increased base fraction in the ROM, the rate of tertiary feed production will increase. The tertiary plant performance and product yields are not expected to change. The impact of the new ROM fragmentation on the Bivitec will need to be closely monitored, particularly if the secondary feed rate is significantly increased and the feed becomes very fine. The impact of the changes in ROM size distribution on excavation and productivity will need to be closely monitored in the implementation phase to confirm these results. Similarly the next 3-month monitoring period will be used to assess the impact of the new blast design guidelines on the plant performance.

INTRODUCTION

The production of a mineral commodity is a two-stage process involving mining to extract the commodity and processing to convert the commodity into a marketable end product. Traditionally, these two stages have been viewed as self-contained entities. In fact, great strides have been made over the years in the stand-alone optimization of each entity. Unfortunately, mining and processing are intimately linked, particularly in the area of particle size reduction. Thus, optimizing each stage separately without considering the total system often misses potential economic benefits and energy savings. This is particularly true in the aggregates industry where the sole objective is to produce crushed stone of various sizes. Since 1998, researchers at the Julius Kruttschnitt Mineral Research Centre (JKMRC) in Queensland, Australia, have been conducting Mine-to-Mill optimization research at operations throughout the world. Mine-to-Mill, as the name implies, is the holistic approach to mining and mineral processing. Developed at the JKMRC, it provides a complete fragmentation and size reduction solution to maximize benefit. The entire operation is taken into account, from blasting to comminution, in order to optimize the size reduction process. Mine-to-Mill optimization has been successfully applied in gold, copper, and lead/zinc operations throughout the world producing increases in throughput from 5 – 18% and cost reductions in the neighborhood of 10% (Atasoy et al., 2001; Grundstrom et al., 2001; Hart et al., 2001, Karageorgos et al., 2001, Paley and Kojovic, 2001, Valery et al., 2001).

The aggregates industry appears to be a perfect candidate for Mine-to-Mill optimization since its main focus is particle size reduction through blasting and crushing. The aggregates industry represents the largest segment of the U.S. mining industry accounting for more than two-thirds of the non-fuel minerals produced, and over half of all mined commodities when coal is included (Tepordei, 1999). In fact, 1.5 billion tonnes of crushed stone are produced annually in the U.S., at a value of nearly \$9 billion (Tepordei, 2002). Since a typical crushed stone quarry can consume between 1.7 – 2.2 kWh/t (Smith, 2003), over 2.5 billion kWh of electrical energy are consumed per year by crushed stone production. Clearly, if there is a segment of the mining industry where energy saving research can have an impact, it is the aggregates industry.

Unfortunately, this major segment of the U.S. mining industry has been virtually ignored by researchers and funding agencies. Furthermore, Mine-to-Mill optimization has yet to be applied to the aggregates industry. The aggregates industry presents a unique challenge in that, unlike the metal mining industry, its goal is particle size control as opposed to particle size reduction. Whereas increased particle size reduction during blasting may be a benefit in the metal mining industry, it may actually be a detriment in the aggregates industry if the increased blasting energy results in the creation of fine particles that cannot be marketed. Thus, additional research is needed in order to translate the Mine-to-Mill approach to the aggregates industry.

The purpose of this project is to adapt the Australian Mine-to-Mill optimization technology to the U.S. aggregates industry. The project is being carried out over two-years by a team consisting of (i) Virginia Tech - project manager and prime contractor,

(ii) Contract Support Services/JKTech representing JKMRC - subcontractor and provider of Mine-to-Mill expertise, (iii) Luck Stone - the 12th largest U.S. crushed stone producer providing locations for the test work, (iv) Austin Powder - providing support on blasting, and (v) Mellott Enterprises, Inc. - representing major equipment manufacturers and providing support on crushing and screening. The work is being conducted at two Luck Stone quarries, the Bealeton Quarry near Fredericksburg, Virginia, and the Pittsboro Quarry, near Chapel Hill, North Carolina.

The project entered its second year with a scoping study at the Pittsboro quarry. This was followed by a detailed plant audit and size analyses of the samples collected. Finally, the data were used to create models for use in simulation programs to determine the most appropriate blasting and plant operating practices that would minimize energy consumption. Simulations from these programs were compared to base-line data established by monitoring current Luck Stone practices at Pittsboro over a period of approximately three months. The following report serves to summarize the work at the Pittsboro site and to present the recommended Mine-to-Mill approach that is currently being implemented and evaluated.

EXPERIMENTAL

The Pittsboro Quarry is located off of route 15, south of Chapel Hill, North Carolina. The property is owned by the 3M Corporation but the quarry is operated by Luck Stone. With 3M on site as a major customer, the quarry began to market material to the public in April of 2002, and has continued to grow its presence since that time. Pittsboro mines a green-colored andesite utilized on site by 3M for the production of roofing shingle granules. The plant also blends volcanic tuffs with basalt and several other volcanic types for aggregate use. The highly variable nature of the geology at the Pittsboro Quarry makes this site particularly challenging for Mine-to-Mill optimization. Pittsboro produces about 1.6 million tonnes of crushed stone products per year.

Pittsboro Site Test Work – Scoping Study

Test work at the Pittsboro site began with a scoping study in March 2005 to evaluate current practices and potential areas for improvement. An aerial view of the quarry is shown in Figure 1. As shown, the areas marked “3M Andesite” are mined, crushed to below 90 mm, and sent to 3M for their on-site roofing granule manufacturing process. All other rock is processed by Luck Stone and sold on the commercial market.

The Mine-to-Mill optimization study at the Pittsboro Quarry is focused primarily on the Luck Stone part of the operation; although some side benefits may be obtained by 3M as a result of this work. Luck Stone is currently moving into an area in the northwest corner of the quarry that contains a basalt-type rock. They expect to be mining this material for several years and hope to ultimately access some additional andesite for use by 3M. It is this region of the quarry that is of primary interest in the present study.

Figure 1. Aerial view of the Pittsboro Quarry showing the areas of andesite mined for 3M. The northwest corner of the quarry is the area being studied in this investigation.

Blasting at the Pittsboro Quarry is normally carried out using a 5.5 m x 4.3 m pattern (burden x spacing) although a 4.6 m x 4.6 m pattern is used on harder materials. These patterns are typically used on 21 m benches with 4.8 m of stemming and a hole diameter of 165 mm. Blasting is typically conducted 3 times per week with a typical shot of 30,000 tonnes at a powder factor of 0.35 kg/t. As compared to the Bealeton quarry, oversize material is generally not an issue at Pittsboro (less than 2% of a typical shot) with the hydraulic rock breaker being required less than 0.5 hour per day.

Figure 2 gives a schematic of the Pittsboro plant layout and material flow. The Pittsboro plant currently produces around 1.6 million tonnes of crushed stone products per year, of which two-thirds would represent 3M material. Three main rock types are present including andesite, which is fed to the 3M plant, and dacite tuffs and basalt which are fed to the Luck Stone plant. A significant portion of the ore body is massive, particularly in the lower lifts. In the upper lift the rock can be highly structured. Andesite tends to be found in the massive zones.

Figure 2. Pittsboro plant flowsheet.

Mine haulage equipment consists of three trucks and two loaders. The mine also has a 165 mm diameter blasthole drill. Excavated ore is trucked to the primary crusher hopper/grizzly feeder. The grizzly oversize reports to the primary jaw crusher, which has a capacity of approximately 475 tph at the typical 146 mm closed side setting. The grizzly has a 165 mm opening at the end of the tapered bars. Grizzly undersize and crushed ore report to a conveyor belt ahead of a Rip-Rap screen fitted with 230 and 280 mm holes. The Rip-Rap screen removes the slabby oversize that typically has a thickness just under the primary crusher gap, but can be 280 to 600 mm in length and width. Unless removed, this oversize can bridge the feeders and secondary crushers downstream. The Rip-Rap undersize material reports to a stacker that can place the crushed ore into one of three Secondary Plant surge piles. Pile A is designated for 3M only, B can feed either 3M or Luck Stone (LS), and C is for Luck Stone (LS) only. A sensor, installed as part of this study, automatically tracks the stacker position and thereby quantifies the operation of the primary crusher on both 3M and LS rock types. The secondary piles each have over 6,000 tonnes of live surge capacity.

The LS secondary plant is fed by two apron feeders, the combined feed (C11) reporting to an inclined triple-deck vibrating screen. The purpose of the screen is to reject the material too coarse for the tertiary plant, and also remove the -38 mm material, which contains all the weathered material, known as Base or Crusher Run. Due to problems in meeting North Carolina specifications on the plasticity of this product, Luck Stone has upgraded the secondary plant which now includes a Bivitec screen to remove the clayey fines from the Base (C31/32). The apertures on the top deck of the Bivitec are nominally 19 mm, whereas the bottom deck has apertures ranging from 3 to 6.5 mm. Since the capacity of the Bivitec screen is limited to around 450 tph, there is a provision to by-pass the screen (C14A-C14B-C14C). The nominal 90 mm top deck oversize (C12) material reports to a feed bin ahead of a cone crusher. The 63 mm middle deck acts to reduce the load on the nominal 38 mm bottom rubber deck screen. The crusher product (C13) recycles back to the top deck screen. The bottom and middle deck oversize reports (C16) to the Tertiary Plant surge pile.

The Bivitec top deck has 9 blend gates which allow Luck Stone to tune the grading on the Base product to meet the unusual North Carolina regulation that controls both the fines and coarseness (ie. 94% -25 mm and 3-6% +25 mm). The remaining fraction of the top deck is conveyed to the Tertiary Plant feed belt (C30 to C16). Since the feed to the secondary plant is typically limited to 540 tph and the coarseness of the feed is quite variable, the plant tends to cycle during which the crusher feeder stops every few minutes to allow oversize material to fill the bin. This stop-start operation consequently results in additional wear on the crusher and reduced efficiency in screening. The plant is controlled using a strategy that looks at the feed rate set-point plus the crusher amps, feed bin level and crusher bowl level.

The tertiary plant is fed by four apron feeders, the combined feed reporting to a cone crusher on a variable speed belt (C17). The crusher is also fed by the recycled top deck screen oversize (C19). The crusher product reports (C18) to an inclined triple-deck vibrating screen. The screen apertures are configured on the basis of the

production setup (i.e., only products #67 and #78). During the August 2005 audit, the following apertures were used:

Top Deck -	40% rubber (22 mm openings) and 60% wire (22 mm openings)
Middle Deck -	60% rubber (12.7 mm openings) and 40% wire (12.7 mm openings)
Bottom Deck -	100% rubber with a combination of 5/5/3.5/5/5 mm openings

The middle and bottom deck oversize reports to the C22 belt, which is fed to an inclined triple-deck tertiary wash vibrating screen. The bottom deck undersize is the dust (C20). The plant is controlled using a strategy that looks at crusher amps and bowl levels, and feed tank level. The feedrate to the plant is allowed to vary to maintain the amp and levels set-points.

The wash screen has blend gates on all three decks, allowing four setups to be configured depending on the target products. During the August audits, only #78 (C26/27) and #67 (C24/25A/25B) products were produced. These two products report to stackers; while the #5 (C23) product, which is not typically produced, reports directly to its own stockpile. The following apertures were in place during the audits:

Top Deck -	50% rubber (22 mm openings) and 50% wire (22 mm openings)
Middle Deck -	100% polyurethane (12.7 mm openings)
Bottom Deck -	100% polyurethane (0.5 mm openings)

The bottom deck screen undersize reports to the fines sump/laundry collection system, which then pumps the washed fines to a settling pond.

During the scoping study, belt speed measurements were taken at all sampling points throughout the plant, and estimates of belt loads were used to determine the length of belt that would be required to provide a sufficient sample size. Crusher sets were also determined using lead weights lowered into the crushing chambers.

Pittsboro Site Test Work – Analysis

Blast Monitoring and Analysis: In order to collect data to calibrate the blasting and comminution models, it is necessary to carefully monitor all relevant aspects of a blast. On August 10, 2005, blast 8605, was used for this purpose. The pattern was nominally 5.5 m x 4.3 m (toe burden x spacing) with 4.8 m of stemming in a 21 m bench. Drill holes were angled to protect the back wall, which means the burden and spacing were referenced to the toe, not the collar. Figure 3 is a plan view of the pattern generated using *JKSimBlast*. The face of the blast was completely clean (Figure 4).

It is important that the input parameters of the blast fragmentation model correspond with the actual blast parameters that were implemented. The following list summarizes the data that were collected for this blast.

- All hole collars and crest lines were surveyed to determine the actual burden and spacing.
- Hole depths, charge lengths for each product, and stemming lengths were obtained from detailed loading sheets.
- Face profiling was used to determine face burden.
- The velocity of detonation (VOD) was recorded for selected holes.
- Every hole was bore tracked to quantify the deviation from vertical.
- Fracture frequency of two faces adjacent to the blast was measured to estimate the *in situ* rockmass structure.
- Intact rock properties were obtained from measurements previously performed at Virginia Tech.

Figure 3. Plan of Blast 8605 with surface initiation; inset shows face profile.

Figure 4. Northerly view of blast 8605.

An overview of the blasting practice and implementation in shot 8605 found the actual design to be somewhat tighter than planned (4.3 x 3.8 m at mid bench). This smaller spacing coupled with the highly energetic emulsion of HydroMite 4400, necessary in the wet holes, resulted in very fine fragmentation in what appeared to be fractured weak rock (see Figure 5). Samples from the C2 belt revealed rocks with a variable strength from 20 to 200 MPa, supporting this initial assessment. The throughputs observed on the 8605 shot material were significantly higher than the typical daily average in the plant, attesting to the unusual nature of this material. The muckpile was free of any oversize, with the exception of one large rock that fell out of the adjoining face.

Figure 5. Photograph of blast 8605 soon after initiation clearly showing minimal stemming region and good face movement; second photo shows muckpile.

Plant Audit: The aim of the plant audit was to calibrate the JKMRC blast and process plant models based on current practices at Pittsboro. These models would then be used in a simulation study to explore potential new blast design(s) and possibly, operating strategies in the plant.

Since a significant proportion of the mining and processing at Pittsboro is dedicated to 3M, it was decided that the audits should include both 3M and LS rock types. To this end, the primary and secondary audits included one survey with 3M feed material. After sufficient material from the test shot was crushed and stockpiled, the team moved to the LS secondary plant.

The jaw crusher feed size distribution was determined using the Split image analysis on trucks sent to the crusher ahead of each survey. The last truck dumped into the grizzly feeder before the C2 belt was stopped for sampling was assumed to represent the feed to the crusher.

An estimate of the Rip-Rap oversize was made from hand measurements of the dimensions for 10 pieces of rock. The flowrate was estimated by counting the number of pieces that discharged to the stockpile over a 5 minute period.

As far as the secondary plant, its operation post the upgrade and installation of the Bivitec screen was still under investigation by the operations staff when the MTM team arrived at site. The configuration of the screen apertures on the Bivitec screen was recognized as one of the key operating variables and several adjustments had been made to better distribute the load between the top and bottom decks. It was also clear that the maximum feedrate to the screen was limited to around 450 tph, which meant that surveys on fine feeds like that expected from the test shot (8605) would require the Bivitec to be by-passed at feedrates in excess of 450 tph. The only way to test the plant on coarser feed from the test shot material was to wait for the stockpile to run down, when the fines would be depleted. Hence the audit plan for the secondary plant required 7 surveys to quantify the effects of feed size (stockpile level), feedrate and crusher gap. The tertiary audits were run after sufficient material was processed through the secondary plant. Figure 6 shows the plant layout with the belt sample points indicated by red circles.

The primary crusher survey was conducted in open circuit mode, at the typical closed side setting (CSS) of 146 mm and 181 mm open side setting (OSS). Both the secondary and tertiary surveys were conducted in closed circuit mode, as close as possible to steady state, at nominal CSS settings (secondary – 51, 44 and 38 mm; tertiary – 28, 22 and 19 mm). As noted, the cyclic nature of the secondary plant forced the sampling to take place about half way through a typical cycle for five of the seven surveys. Hence the loads on the belts in these surveys were not expected to be stable. The two surveys in which the plant was almost at steady-state had by far the coarsest feed. The tertiary plant was much more stable so it was possible to run the plant in near steady-state conditions before each survey. Once the performance of the individual unit

operations was calibrated, changes in ROM feed sizing could then be investigated independently at any combination of feedrate and crusher settings.

Figure 6. Pittsboro plant sampling layout.

1. The primary crusher product was sampled first at the prevailing feedrate at the time of sampling (approximately 900 tph for the 3M andesite and 1400 tph for the Luck Stone basalt). Approximately 11 m of material was removed from the C2 belt for the 3M sample, both coarse rock (>75mm) and fines, and approximately 8.5 m of material was removed for the Luck Stone sample. The coarse rock was processed on site using a set of square frames, sized from 75 mm to 212 mm. The fines samples were placed into barrels and returned to Virginia Tech for detailed sizing down to 75 microns. The crusher gap was measured by Luck Stone staff before the crusher was started that same morning.

LS	1386 tph, F80=178 mm, P80=113 mm (46% -38 mm), 0.03 kWh/t
3M	882 tph, F80=341 mm, P80=151 mm (34% -38 mm), 0.10 kWh/t

The Luck Stone shot was very fine and consequently the throughput was very high. As discussed previously, the main reason for the fine fragmentation was the use of a highly energetic emulsion of HydroMite 4400 and slightly smaller spacing in the blast pattern in a fractured weak rock. The belt cut samples revealed rocks with a variable strength, from 20 to 200 MPa. To match this fragmentation, the JKMRC blast simulations suggest the rock type in the 8605 shot would need to be 60/40 hard basalt/softer weathered material. This is not unreasonable considering the very high throughputs seen in the August test shot (higher than the maximum daily average typically observed). The 3M shot was more typical and resulted in a throughput close to the typical average. The Split sizing estimates for the jaw crusher feed are shown in Figure 7.

Figure 7. Primary crusher feed and product size distributions.

2. For the LS secondary plant audits, the aim was to test the effect of feed coarseness, gap and crusher load. The normal setting (44 mm) was tested at a 450 tph feedrate setpoint, considered by the plant operators to be appropriate for the fine feed size conditions (high stockpile) and Bivitec limit. The feedrate was then increased to 590 tph, which was considered too high a load for the Bivitec, considering the fines level in the feed. Three settings were tested; 44, 51 and 38 mm. The plant was then allowed to run overnight to bring the pile down and thereby coarsen the feed. The next morning the plant was surveyed at 540 tph and the normal gap setting, with a low stockpile level expected to provide a much coarser feed. The gap was then increased and another survey at the 590 tph throughput was carried out. The final survey was conducted at 450 tph, low stockpile and normal gap setting, with the Bivitec online. To simplify the survey analysis, no dust material was returned via belt C28. The crusher gaps were measured using lead balls before each survey. Figure 8 shows the feed size distributions during the seven surveys, highlighting the very fine feed in five of the surveys. Note that survey 5, which was the first one after the stockpile was run down, had the finest feed of the set. The mass balanced results from the surveys are summarized in Table 1, which includes the tonnage rates, feed size F80 values and specific energy consumptions. The predicted screen oversize is included for comparison with the actual crusher feed (C12). Only in surveys 6 and

7 were the screen oversize rates close to the crusher feed rate, and therefore close to running at steady-state.

Figure 8. Secondary plant feed size distributions.

Table 1. Summary of Secondary Plant Survey Results.

Survey	Pile Level	CSS (mm)		C9	C12	C13	C29	C16	Screen O/S	kWh/t
1	Hi	44	tph	483	147	147	307	222	102	0.08
			F80 (mm)	63	127	64	17.3	57.8	133	
2	Hi	44	tph	595	313	313	453	317	136	0.13
			F80 (mm)	67	161	47	16.1	54.9	167	
3	Hi	51	tph	609	349	349	456	359	144	0.15
			F80 (mm)	69	125	56	16.8	58.4	154	
4	Hi	38	tph	579	343	343	463	290	168	0.15
			F80 (mm)	71	169	41	17.7	52.3	15.3	
5	Lo	44	tph	609	309	309	522	332	64	0.10
			F80 (mm)	51	118	49	16.4	57.1	128	
6	Lo	51	tph	583	362	362	223	380	341	0.21
			F80 (mm)	131	159	60	17.7	60.3	154	
7	Lo	44	tph	463	158	158	160	301	161	0.09
			F80 (mm)	87	147	59	19.8	59.1	124	

3. Only one survey was conducted on the 3M secondary, at the normal setting of 51 mm and feedrate of 635 tph. The single deck screen aperture was 100 mm. The survey consisted of plant feed (C4), crusher product (C6B) and final product (C7).

The raw results from this survey are as follows:

633 tph, F80=143 mm, P80=58 mm (Figure 9), 0.204 kWh/t, crusher recycle=46%

Figure 9. 3M secondary plant product size distribution.

4. Three audits were carried out on the LS tertiary section. The CSS settings used were 28, 22 and 19 mm. The approach was to test the plant performance at each setting with the plant in automatic control on amps and crusher feed level. Hence the feedrate varied since the controller attempted to keep the crusher choke fed. For each audit, the plant feed (C17) and all product belt samples (C18, C19, C20, C22, C24 and C26) were collected. The wash screen bottom deck undersize was not sampled. The feed size in the three surveys was very consistent, as evidenced from Figure 10. The raw data for the surveys is summarized in Table 2.

Table 2. Summary of Tertiary Plant Survey Results.

Survey	CSS		C17	C19	C20	C24	C26	kWh/t
1	28 mm	tph	94	88	18	53	11	0.87
		F80 (mm)	54		2.6	17	8.1	
2	22 mm	tph	135	50	28	71	13	0.81
		F80 (mm)	53		2.7	17	8.3	
3	19 mm	tph	145	21	37	78	16	0.89
		F80 (mm)	53		2.8	16	8.6

Figure 10. LS tertiary plant feed size distributions.

The survey results clearly show that on average the crusher capacity when choke fed is in approximately 180 tph. The second survey appears to be close to the optimum in terms of throughput, specific power consumption and product yield. The results also highlight a consistent discrepancy between feed and product weightometers. On average the feed belt C17 is 12% higher than the sum of the product belts.

Throughout the plant audit phase, all the conveyor belt speeds were measured prior to sampling. Belt cut lengths were selected on the basis of statistical requirements, considering the size of rocks on each belt, the load and conveyor speed. The belt samples from the secondary and tertiary audits were placed into barrels and buckets and returned to Virginia Tech for detailed sizing, down to 75 microns. The coarse rock from the secondary surveys (C9 and C12 in the LS plant, and C4 in the 3M plant) were processed on site using a set of square frames, sized from 75 mm to 212 mm. Appendix 2 gives a summary of the crusher settings and samples collected during the audits. Appendix 3 gives a full size analysis of the samples collected.

RESULTS AND DISCUSSION

Pittsboro Site Test Work – Modeling and Simulation

Fragmentation Modeling: When the JKMRC commenced their original Mine-to-Mill research, one of the objectives of the fragmentation modeling aspect was to improve the prediction of the fine end of the muckpile size distribution. Model development advanced along two fronts. The philosophies of these two approaches are similar in that they predict the fine and coarse ends independently but the approaches are very different. The Crush Zone Model (CZM) (Kanchibotla et al, 1999) uses a semi-mechanistic approach to calculate the volume of crushed material around each blast

hole while the Two-Component Model (TCM) utilizes small-scale blasting to experimentally derive the fine end of the distribution. Both continue to use the Kuz-Ram model (Cunningham, 1983) – or a modification of it – for the coarse end. The blast fragmentation modeling for this project was done using the CZM approach.

Analysis of the data collected during the blast monitoring and assessment of blast 8605 resulted in the following input parameters for the JKMRC blast fragmentation model (Table 3).

Table 3. Fragmentation Model Input Parameters for Blast 8605.

PATTERN	8605
Bench Height (m)	21
Burden (m)	4.3
Spacing (m)	3.8
Hole Diameter (mm)	165
Hole Depth (m)	22
Sub-drill (m)	1.0
Stemming Height (m)	4.8
ROCKMASS	
Rock Type	Basalt
Specific Gravity	2.79
Young's Modulus (GPa)	67
UCS (MPa)	200
Mean Block Size (m)	0.3
EXPLOSIVES	Bottom Deck
Type	HydroMite 4400
Length (m)	17.3
Mass (kg)	452
Specific Gravity	1.22
VOD (m/s)	5500
RWS	95
Powder Factor (kg/m ³)	1.31
Powder Factor (kg/t)	0.45

The model-predicted size distribution for shot 8605 (solid line) is shown in Figure 11, together with the Split measured primary crusher feed as determined from 10 images of different truck loads heading up to the crusher pad. The C2 sample has been included in the chart since it should reflect the fines (<10 mm) in the muckpile, assuming the sample is representative of the full shot. The ROM size distribution shows around 13.7% less than 6.3 mm, and 34% less than 38 mm.

Figure 11. Pittsboro ROM Fragmentation for Blast 8605, model prediction and Split size analysis.

Plant Modeling: The modeling of the plant operation at the Pittsboro Quarry was a three stage process that involved determining the breakage characteristics of the ore, mass balancing the samples collected during the plant audit, and fitting the breakage data and mass-balanced sample data to the model equations contained in JKSimPlant.

Impact breakage tests were performed on selected samples of the Pittsboro ore to characterize the breakage behavior of the rock. Since significant variability was observed in the geology at the Pittsboro Quarry, the impact breakage testing was extended to characterize five different rock types observed at the site (See Figure 12). The data obtained from these tests were used in conjunction with the equation:

$$t_{10} = A \left[1 - e^{(-b.Ecs)} \right]$$

which relates the breakage behavior of the ore to the specific comminution energy. In the above equation, t_{10} represents the percent of material in the product from the impact breakage test that is finer than one tenth of the original rock size prior to breakage. Ecs represents the specific comminution energy (kWh/t) determined from the mass of the weight and the height from which it is dropped when the impact breakage test is performed, and 'A' and 'b' are model parameters which are fitted to the experimental data. Generally, parameter 'A' represents the maximum level of breakage for a

particular ore type and 'b' is related to the hardness of the ore with lower values of b indicating a harder ore. As there is some interaction between 'A' and 'b' in the impact breakage equation, the JKMRC uses $A*b$ for comparison because it is better defined. $A*b$ is the slope of the curve at 'zero' input energy, Ecs. The results of the impact breakage tests are summarized in Table 4.

Figure 12. Examples of Pittsboro ore variability; test shot face and C2 sample.

Table 4. Summary of Ore Breakage Test Results.

Ore Type	A	b	SG	$A*b$	UCS* (MPa)	SG	UCS (MPa) – from Point Load Tests (PLT)
Survey Samples (from C2 belt cut)						Spot Samples (from C2)	
LS	56	0.79	2.79	44.2	212		19, 66, 97, 183
3M	53	0.69	2.83	36.2	303		19, 58, 112, 124, 142, 288
31.5 x 26.5 mm samples only							
LS (composite)	73	0.60		43.8	216	2.75	204
3M (composite)	72	0.44		31.8	385		
Basalt	66	0.66		43.8	216		
Dacite	100	0.30		30.0	424		
Miscellaneous	71	0.56		39.9	255		
Tuffs	92	0.37		34.2	336	2.78	88
Weathered	55	1.15		63.5	111		

UCS - estimated from A and b parameters using JKMRC proprietary correlations.*

The characterization results are as expected in terms of the LS and 3M samples, and it appears that the five different ore types identified by the research team are also consistent. Clearly the 3M andesite is harder than the LS basalt. The weathered group is quite variable and has the lowest UCS with an average of around 90 MPa, while the basalt is much harder, with typical values around 200 MPa. The tuffs are in the same range as the 3M andesite, which, from previous measurements, has a UCS around 275 MPa. The miscellaneous ore type appears to be harder than the basalt but somewhat

weaker than the 3M andesite and the dacite samples. The results on the spot C2 samples suggest that both the LS and 3M materials contain some softer rocks, but in general have a majority of the main rock type, basalt or andesite. The full and partial test reports for the drop-weight tests can be found in Appendix 1.

Following characterization of the rock, the data analysis and modeling was broken into four parts:

1. Primary: Luck Stone and 3M - 1 survey on each feed source
2. Secondary: Luck Stone - 7 surveys; 3M - 1 survey
3. Secondary: Bivitec - 2 surveys
4. Tertiary: Luck Stone - 3 surveys

In the case of the primary plant, where mass balancing was not possible, the only accurate sample was C2. The crusher feed size distribution was estimated using Split analysis of truck loads, with the last truck tipped into the grizzly feeder assumed to represent the feed responsible for the C2 result. As noted previously, the Rip-Rap oversize was not quantified precisely, and it was not possible to sample the grizzly oversize and undersize. The models for these three pieces of equipment relied on previous knowledge and the design criteria for the two screens and crusher. Hence the main parameter to be determined was the crusher t_{10} which describes the degree of ore breakage in the machine. Figure 13 shows the fitted and measured results using the calibrated JKSimPlant model for the Luck Stone feed audit.

Figure 13. Comparison of audit and fitted sizing results for Pittsboro primary plant survey – LS side (@ 1385 tph, gap=146 mm).

Before the model calibration could start on the remainder of the plant, the secondary and tertiary audit data had to be mass balanced to provide consistent information around the screens, which were in closed-circuit with the crushers. The belt cuts and conveyor speeds provided initial estimates of the tonnage rates on each belt just prior to the plant being crash stopped, and weightometers on the main plant feed conveyors were assumed to be correct. Since the belt cuts were sized to be statistically large enough for each product (Gy, 1976), with the exception being the crusher feed, the resulting sizing data from each sample was considered to be representative. Due to the large oversize rocks present in the crusher feed, a statistically valid sample would have required around 25 tons. Hence the 400 kg samples were not expected to provide reliable data at the coarse end (>125 mm). Rather, the mass balance was expected to yield a good indication of the coarse end given all other samples and estimated flows.

The LS secondary plant data around the crusher showed the most variation from the belt cut tonnage rates, which is not surprising considering the cyclic nature of that plant. Consequently the circuit was split into two parts (see Figure 14), and the data were mass balanced assuming the C13 rate represents the actual crusher feed rate, whereas the top deck scalping screen oversize was back-calculated. This approach was successful in allowing the other streams to be easily balanced, and confirmed the extent of imbalance in the flows around the crusher (as shown in Table 1), with only survey 7 having a screen oversize rate that matched the crusher feed rate.

Figure 14. Example of LS secondary plant with split flowsheet concept used in mass balancing and model fitting.

Figure 15 is an example of the balanced and fitted sizings from LS audit 7, showing a very close agreement. The key plant flows are summarized in Table 5.

Figure 15. Comparison of audit and fitted sizing results for Pittsboro secondary plant survey 7 – LS side (@ 463 tph, gap=44.5mm).

Table 5. Comparison of Audit and Fitted Tonnage Rates for Pittsboro Secondary Plant – LS Side (Survey 7 @ 463 tph).

Circuit Stream	Feed Rate (tph)	
	Balanced	Fitted
Sec. Plant Feed (C9)	463	463
Sec. Crusher Product (C13)	158	158
Tertiary Feed (1.5" o/size, C16)	301	309
Crusher Run (1.5" u/size, C29)	160	163

The Bivitec screen was handled separately due to the complexity of the system. The double deck screen, with variable apertures down the 8-meter length posed a difficult problem since no single JKSimPlant model was capable of describing the performance of such a screen. Also, the screen flexing is suspected to cause the bottom deck apertures to be ‘stretched’ during operation, which would change the effective cut-size. Furthermore, the top deck has blend gates which control the fraction of oversize that reports to the tertiary plant feed surge pile and crusher run.

To model this system, the screen was represented in JKSimPlant as five separate decks in series, with a reduced efficiency in each section. The top deck oversize of the first section reports to the second top deck section, whilst the undersize reports to the first section of the bottom deck series, as illustrated in Figure 16. The model was developed using surveys 1 and 7, which only had flow and sizing data on C29 (screen feed), C14C (crusher run), C30 (tertiary feed) and C31 (waste).

The model was based on a simple efficiency curve, the parameters of which were selected to reflect the short screen sections and apertures used in each section. Since there were no intermediate data to calibrate the parameters for each section, the solution was based on previous JKMRRC screen modeling experience. The model was found to fit the data very well (see Figure 17), considering the complexity of model and assumptions made regarding top deck blend gates. The model was considered adequate for fine tuning the process and Mine-to-Mill simulations.

Figure 16. Representation of the Bivitec screen using 5 screens in series, both top and bottom decks modeled separately.

Figure 17. Comparison of audit and fitted sizing results for Bivitec screen (Survey 7 @ 161 tph screen feed rate).

The 3M secondary plant was mass balanced in closed circuit since the plant was able to run for long periods without the need for the crusher to stop. The model parameters were consistent with the 51 mm crusher gap and 100 mm screen aperture. Figure 18 shows an example of the balanced and fitted sizings.

Figure 18. Comparison of audit and fitted sizing results for Pittsboro secondary plant survey – 3M side (@ 633 tph, gap=51 mm).

The tertiary plant data balanced well since the plant was close to steady state prior to each crash stop. The variation from the belt cut tonnage rates was small, as expected. However, a discrepancy in the weightometers was noted suggesting there was an error in at least one of the product weightometers. To facilitate the analysis and modeling the circuit was split into two parts: Dry and Wet (as shown in Figure 19).

Figure 19. LS tertiary plant with split flowsheet concept used in model fitting.

Since there were no data on the middle deck, its parameters were based on previous knowledge of similar screen decks. The tertiary crusher and the screen model for the top and bottom decks in the dry plant were fitted together. The wet plant had limited data, requiring parameters to be fixed for the bottom deck (0.5 mm) and top deck (22 mm). The blend gates were a source of doubt since the setup differed from normal operation during the survey (2 open/4 closed vs. 3 open/3 closed). Hence the only model fitted in the wet plant was the screen model for the middle deck. Figure 20 shows the balanced and fitted sizings from survey 2, showing a very close agreement. The flows in the plant are summarized in Table 6.

Once the breakage characteristics of the ore had been determined and the data acquired through the plant audit had been mass balanced, this information was used in conjunction with the JKSimPlant program to create the mathematical representation of the Pittsboro plant.

Figure 20. Comparison of mass balance and fitted sizing results for Pittsboro tertiary plant (Survey 2 @ 135 tph, gap=22 mm).

Table 6. Comparison of Audit and Fitted Tonnage Rates for Pittsboro Tertiary Plant (Survey 2 @ 135 tph).

Circuit Stream	Feed Rate (tph)	
	Balanced	Fitted
Ter. Plant Feed (C17)	135	135
HP300 Product (C18)	221	212
Recycle (0.875" o/s, C19)	97	77
Dust (0.18" u/s, C20)	29	27
#5 (C23)	-	-
#67 (C24)	84	83
#78 (C26)	28	25
Waste (Pond)	0.09	0.07

The Anderson/Whiten crusher model (Napier-Munn et al, 1996) was used to model the Pittsboro crushers, based on the settings and ore breakage characteristics obtained from drop-weight test on the survey samples. For conventional reciprocating crushers such as jaw, gyratory and cone units these characteristics are represented by 3 parameters (K_1 , K_2 and T_{10}). These ideally equal to the closed side setting (CSS), open side setting (OSS) and the degree of size reduction that rock(s) undergo each time the crusher completes a cycle in its operation respectively. In practice factors such as liners design, wear and the shape of the product influence the actual values of these parameters. Tables 7, 8 and 9 list the crusher parameters and key operating conditions for the plant audits at Pittsboro. In the case of the primary crusher, the Split predicted

ROM size distribution taken from the last truck dumped before C2 was stopped for sampling was assumed to be the feed to the grizzly feeder.

Table 7. Summary of JKSimPlant Primary Crusher Model Parameters and Operating Conditions.

Parameter	Luck Stone	3M
Crusher Settings	CSS = 146 mm Throw = 36 mm	CSS = 146 mm Throw = 36 mm
K ₁	146	146
K ₂	365	365
T ₁₀	8.1	7.0
Plant Feed (tph)	1410	921
Plant F80 (mm)	188	328
Crusher Feed (tph)	400	361
Crusher F80 (mm) - pred	324	501
Crusher P80 (mm) - pred	185	192
Power (kW)	73	91
kWh/t	0.05	0.10

The primary crusher parameter K₂ is unusually high and, assuming the predicted ROM feed size distribution is valid, suggests the crusher is allowing large thin rocks to pass into the product without being broken. This is a common feature of jaw crushers which treat materials that fracture into ‘slabby’ pieces. The Rip-Rap screen removes these pieces before the secondary surge pile. The T₁₀ values are within the expected range for this type of crusher and feed size range. The LS audit reflects a much finer feed, as noted previously, resulting in a 50% higher overall plant throughput.

The secondary crusher parameters in Table 8 are consistent with the secondary crusher models derived from the Bealeton June 2004 audit. As noted earlier, the very fine feed in six of the seven LS audits resulted in a wide range of performance in terms of the specific energy consumption and yield to the tertiary plant surge pile. Clearly if the feed is too fine, the yield to the tertiary plant is reduced, and the feed to the Bivitec screen will be commensurately increased. The results also point to a difference in the ore hardness between the LS and 3M feed. At similar feed conditions and crusher gap, the specific energy consumption is higher for the 3M andesite than the LS ore blend.

The performance variation seen in the LS audits suggests that an online feed size monitor might be a worthwhile addition to the existing control instrumentation. The opportunity lies in the option to regulate the feed rate and/or crusher gap based on the incoming feed size. Clearly, if the feed size is coarser, there appears to be scope to increase the feed rate without any risk of exceeding the load on the Bivitec screen. Conversely if the feed is very fine, the controller should be able to figure out by how much to reduce the feed and increase the gap to maintain the highest yield to the tertiary plant without impacting the Bivitec.

Table 8. Summary of JKSimPlant Secondary Cone Crusher Model Parameters and Operating Conditions.

Parameter	Luck Stone							3M
Survey #	1	2	3	4	5	6	7	1
Throughput Set-Point (tph)	450	590	590	590	590	590	450	635
Stockpile Height	Hi	Hi	Hi	Hi	Lo	Lo	Lo	Hi
Crusher Setting CSS (mm)	43.9	43.9	51.8	38.4	44.7	50.8	44.5	50.5
K_1	49.1	48.8	55.5	41.5	49.3	58.7	48.5	56.8
K_2	120.9	87.5	96.5	80.7	85.6	101.8	113.7	119.3
T_{10}	8.5	10.5	12.3	11.4	11.8	10.8	9.0	10.8
Plant Feed (tph)	483	594	609	579	609	582	463	632
Plant F80 (mm)	63.0	67.0	69.0	71.0	51.0	131.0	87.0	139.8
Crusher Feed (tph)	147	313	348	343	308	362	158	330
Crusher F80 (mm)	130	161	135	170	122	159	147	156
Crusher P80 (mm)	63.6	49.6	57.4	42.6	50.1	60.2	60.3	63.9
Power (kW)	39	86	87	109	87	84	44	112
kWh/t	0.08	0.14	0.14	0.19	0.14	0.14	0.10	0.18
Crusher Run (tph and % of total production)	310 (58%)	446 (58%)	445 (55%)	450 (59%)	516 (61%)	233 (37%)	162 (34%)	-
Tertiary Feed (tph and % of total production)	221 (42%)	326 (42%)	361 (45%)	314 (41%)	330 (39%)	392 (63%)	308 (66%)	632 (100%)

The tertiary crusher parameters in Table 9 are different from the previous tertiary models derived from the Bealeton June 2004 audit. The most significant difference was the higher T_{10} values which are synonymous with higher fines generation. The relatively low T_{10} values for the Omnicone and Symons machines at Bealeton suggest these units are very suitable for the aggregate industry that seeks to create minimal fines in the production of closely sized crushed products.

The impact of the crusher gap is clearly evident from the survey data. As the gap is reduced, the fines recycle load drops and the fines generation increases at the expense of a reduced yield of final products. The optimum setting appears to be close to survey 2, where the gap was close to 22 mm.

The Pittsboro results also confirm the trend seen at Bealeton, where the specific energy consumption is by far the highest in the tertiary plant.

Having successfully fitted the models using the secondary and tertiary audits (viz. tph and/or crusher gap), statistical analysis of the relationships between the parameters and operating conditions was carried out. A dependency of the crusher parameters K_1 , K_2 and T_{10} on gap, throughput and feed coarseness was established. These relationships had the form:

$$\text{CrusherParameter} = a + b \times \text{CSS} + c \times \text{TPH} + d \times \text{F80}$$

where a, b, c and d are the regression coefficients in each parameter relationship. These relationships were used in JKSimPlant to allow simulations to take into account changes in gap and/or crusher operating conditions. As expected, the relationships derived from the Pittsboro audits were of similar form to those developed at Bealeton.

Table 9. Summary of JKSimPlant Tertiary Cone Crusher Model Parameters and Operating Conditions.

Parameter	Luck Stone		
Survey #	1	2	3
Gap Setting CSS	27.9 mm	22.4 mm	18.8 mm
K ₁	25.4	19.8	17.0
K ₂	36.8	41.4	34.6
T ₁₀	17.0	17.1	19.3
Plant Feed (tph)	94	135	145
Plant F80 (mm)	53.5	52.4	53.4
Crusher Feed (tph)	201	212	185
Crusher F80 (mm)	42.4	46.0	49.9
Crusher P80 (mm)	23.9	21.0	17.3
Power (kW)	84	109	135
kWh/t	0.89	0.81	0.93
Recycle C13 (tph and % of plant feed)	106 (112%)	77 (57%)	40 (28%)
Dust C20 (tph and % of total production)	17.2 (18.2%)	26.7 (19.8%)	34.8 (24.0%)
#67 C24 (tph and % of total production)	61.3 (65.0%)	82.4 (61.0%)	83.8 (57.8%)
#78 C26 (tph and % of total production)	15.8 (16.8%)	25.7 (19.1%)	26.1 (18.0 %)

The Pittsboro vibrating screens were modeled using simple efficiency curves which are described by three parameters (Napier-Munn et al, 1999):

- α - sharpness of the split
- C - fines split to undersize
- d50c - cut-size, around 70-90% of the aperture depending on efficiency.

Information from the Pittsboro scalp and product screens collected in the audits were used to derive simple relations between the screen load (tph/screen/m) and the efficiency curve parameters α , C and d50c. However, d50c can also be calculated from

the aperture and the α parameter, using a simple design relationship between the aperture and cut-size of the efficiency curve, given the expected screening efficiency.

Tables 10 through 13 summarize the parameters for all screens. In the case of the LS secondary and tertiary surveys, only the average parameters are shown. The screen parameters reflect the apertures and nature of operation of the different screens. The grizzly screen shows a relatively low sharpness of separation (α) for a coarse aperture screen, and reflects the inefficiency of that deck at the very high loads in the LS audit.

Table 10. JKSimPlant Screen Model Parameters- Primary.

Screen	Primary	Primary	Primary
Parameter	Grizzly	Grizzly	Rip-Rap
Nominal Setting	165 mm	165 mm	230/280 mm
Ave Load (tph)	1410	921	1410 - 921
α	5.0	8.5	10.0
C	99.9	99.9	99.9
d50c	150	175	250

Table 11. JKSimPlant Screen Model Parameters – Secondary.

Screen	Luck Stone		3M
Parameter	TD	BD	TD
Nominal Setting	89 mm	38 mm	100 mm
Ave Load (tph)	843	689	962
α	11.5	9.1	13.8
C	99.6	98.6	99.9
d50c	72.7	25.9	86.6

Table 12. JKSimPlant Screen Model Parameters – Tertiary.

Screen	Dry			Wet		
Parameter	TD	MD	BD	TD	MD	BD
Nominal Setting	22.2 mm	12.7 mm	4.5 mm	22.2 mm	12.7 mm	0.5 mm
Ave Load (tph)	200	125	65	99	85	37
α	10.7	8.9	4.2	11.0	10.9	1.5
C	98.6	99.0	97.9	99.9	99.3	85.0
d50c	18.3	10.1	3.4	18.9	9.6	0.17

As noted earlier, the Bivitec screen model (Figure 13) consisted of a series of 5 double deck screen decks in series, each around 1.5 meters in length. The efficiency curve parameters for these sections were appropriately downgraded to reflect the short lengths but still achieve a final separation result commensurate with the performance seen in the two surveys. The cut-sizes for the top deck are consistent with the apertures, whereas the bottom deck cut-sizes are larger than first expected, probably

because the slots were long and the very flexible screen cloth is ‘stretched’ during the operation, as claimed by the manufacturer. This stretching is intrinsic to the screen operation, designed to keep the cloth from blinding.

Table 13. JKSimPlant Screen Model Parameters – Bivitec Screen.

Screen	Top Deck Sections (1.5 m)					Bottom Deck Sections (1.5 m)				
Parameter	1	2	3	4	5	1	2	3	4	5
Nominal Setting (mm)	12.7	12.7	12.7	19.1	19.1	3.0	3.7	3.0	2.0	6.4
Ave Load (tph)	160	109	89	80	59	51	53	46	58	63
α	6.7	6.8	6.8	6.9	6.9	5.4	5.4	5.4	5.4	5.4
C	68.1	69.2	69.7	95.5	96.1	56.3	56.1	56.4	50.8	66.3
d50c	9.92	9.84	9.81	14.7	14.7	4.82	5.33	4.81	3.94	6.43

Statistical analysis of the relationships between the screen parameters and operating conditions was carried out for each deck. A dependency of the screen parameters α , C and d50c on throughput and percent passing the nominal screen aperture was established. For example, in the case of the tertiary dry plant screen top deck, which has a 22.2 mm nominal aperture, the relationships had the form:

$$\text{ScreenParameter} = p + q \times \text{TPH} + r \times \% - 22.2\text{mm}$$

where p, q and r are the regression coefficients in each parameter relationship. These relationships were used to update the parameters in JKSimMet to allow simulations to take into account changes in screen operating conditions, particularly the load on the screen.

Overall, the August 2005 audit information and modeling analysis suggest the following average specific energy consumptions across the three crushing stages at Pittsboro.

Table 14. Comparison of Energy Consumptions for Pittsboro.

Crusher Stage	Luck Stone	3M	Total	(%)
Primary kWh/t	0.05	0.10	0.15	11
Secondary kWh/t	0.13	0.18	0.31	23
Tertiary kWh/t	0.88	-	0.88	66
TOTAL kWh/t	1.06	0.28	1.34	100

The audit results suggest the overall specific energy consumption distribution at Pittsboro is similar to that of Bealeton, with 66% of the energy consumed in the tertiary plant. The primary component is only 11% at Pittsboro compared to 19% at Bealeton, suggesting the Bealeton primary crusher may be undersized for the duty.

Baseline Plant Simulations: The models outlined above were used to construct JKSimPlant baseline circuits for Luck Stone (Primary, Secondary, and Tertiary) and 3M (Primary and Secondary). These flowsheets, shown in Figures 21 and 22, were designed to be used in testing the effect of alternative blast fragmentations and/or equipment configurations on plant performance.

The simulation approach was as follows:

1. The expected ROM size distribution was generated using JKSimBlast, based on rock and blast design parameters.
2. The ROM was input to the primary flowsheet as feed to the plant. The grizzly screen parameters were selected to suit the prevailing feed rate expected. The jaw crusher T_{10} was adjusted in relation to the feed coarseness expected in the grizzly oversize.
3. The primary plant simulation generated an estimate of the feed to the secondary plant. The product from the primary plant was entered into the secondary flowsheet as feed to the plant. The top and bottom deck screen parameters were fine tuned using the simulated loads and coarseness.
4. The secondary plant simulation generated the feed to the tertiary surge stockpile and feed to the Bivitec screen. The Bivitec simulation completed the simulation to give estimates of the base and waste products.
5. The combined stream reporting to the tertiary surge pile from the secondary plant simulation was entered into the tertiary flowsheet as feed to the plant. The top and bottom deck dry screen and middle deck wet screen parameters were fine tuned using the simulated loads and coarseness. The simulation provided estimates of the final products, dust and waste streams.

Figure 21. JKSimPlant baseline flowsheet for Pittsboro 3M plant.

Figure 22. JKSimPlant baseline flowsheet for Pittsboro Luck Stone plant.

Pittsboro Site Test Work – Baseline Monitoring

As a result of lessons learned from Phase I work at the Bealeton Quarry, it was determined that side-by-side comparison tests were not sufficient to quantify potential improvements and energy savings resulting from Mine-to-Mill optimization versus current quarry practice. As a result, a long-term monitoring approach was used to characterize current practices at the Pittsboro Quarry.

Detailed control system data on the Pittsboro plant were provided by Luck Stone on a monthly basis beginning November 1, 2005. This included primary, secondary and tertiary performance data recorded every 10 seconds for each day. The primary stacker position sensor, installed in October 2005, kept track of the rock source so that the

primary crusher performance on Luck Stone and 3M material could be differentiated. Long-term monitoring was carried out for a period of three months, although only 60 days of data out of a possible 92 were recorded due to public holidays, weekends and downtime.

The results are presented for each plant in turn, highlighting the 3-month production totals and monthly production rates, which includes the specific power consumption and product yields where applicable. The distribution of the throughput to each plant over the 3-month period is also discussed.

Primary Circuit: Monitoring results for the primary circuit (see Table 15) suggest 3M takes at least 61% of the material from the quarry. Stockpile B only sees 9% of the material, which can feed both 3M and LS secondary plants. Assuming a 50:50 split on the B pile material would mean 3M is fed around 66% of the feed, which is consistent with the production targets at Pittsboro. In terms of crusher utilization, represented by the Hours Run and Crushed per day, the figures suggest on average the overall utilization is around 85%, or 15% of the time the crusher is not doing useful work.

Table 15. Production Totals for Primary Crushing.

tonnes A	tonnes B	tonnes C	tonnes LS	tonnes TOTAL
241,643	34,331	119,434	153,765	395,408
61%	9%	30%	39%	100%

LS Hrs/Day		Difference	3M Hrs/Day		Difference	Total Hrs/Day		Difference
Run	Crushed	Run-Crushed	Run	Crushed	Run-Crushed	Run	Crushed	Run-Crushed
3.70	3.23	13%	5.40	4.54	16%	9.10	7.76	15%

The production rate information in Table 16 shows the throughput and power consumptions for both Luck Stone and 3M ore. The results show a statistically significant difference between the LS and 3M production rates of around 110 tph, and corresponding lower specific energy consumption (0.10 vs 0.13 kWh/t). This is consistent with the earlier ore characterization test work which suggested the 3M andesite is around 30-40% harder than the LS material.

Table 16. Production Rates for Primary Crushing.

Month	Values	LS tph	3M tph	LS kWh/t	3M kWh/t	LS kW	3M kW
Nov	average	1038	841	0.09	0.14	91	120
Dec	average	945	842	0.13	0.15	122	129
Jan	average	958	921	0.09	0.11	83	99
Total	average	980	869	0.10	0.13	95	116

The variation in daily production rates was also examined to compare the LS and 3M operating statistics. Figure 23 shows the comparison, which includes a histogram chart for the frequency (defined as number of days in 50 stph bins), and a cumulative trendline which shows the percentage of days the daily throughput was at or below a given rate. The charts confirm there is a consistently higher production rate for the LS rock types.

Figure 23. Comparison of frequency distributions for LS and 3M primary crusher throughput rates, 3-month period Nov-05 to Jan-06.

Luck Stone Secondary Circuit: Monitoring results for the Luck Stone secondary circuit (see Table 17) suggest on average that the utilization is only 75%, showing 25% of the time the crusher is not doing useful work. This possibly reflects the cyclic nature of the secondary plant operation noted earlier, in which the crusher is idle for significant periods of time whilst the feed bin level rises into an acceptable operating range for the crusher feed belt to start. Typically the crusher will start and stop five times during each hour of operation, with a 3 minute idle time during each stop. This equates to 15 minutes every hour or 25%; consistent with the 3-month production statistics.

Table 17. Production Totals for LS Secondary Crushing.

Total LS Tonnes	LS Hrs Run/Day	LS Hrs Crushed/Day	Difference Run-Crushed
133,831	6.32	4.73	25%

The production rate information in Table 18 shows the plant throughput and power consumption, crusher feed rate, production rate to tertiary surge pile, and dust feed rate to the base pile. Figure 24 shows the variation in daily production rates over the 3-month period. The results suggest that the plant throughput varies significantly from day to day, evident from the frequency distribution chart. This would further suggest that the feed size variation is significant. On average the yield to the tertiary plant is 47%, which means just over half of the incoming feed reports to base.

Table 18. Production Rates for LS Secondary Crushing.

Month	Values	LS tph	LS kWh/t	Crusher Feed tph	Tertiary Feed tph	Dust Feed tph	Crusher Circulating Load%	Tertiary Plant Yield%	Crusher Power kW
Nov	average	500	0.17	217	248	38	43%	50%	87
Dec	average	390	0.22	172	188	49	44%	48%	84
Jan	average	550	0.15	255	248	59	46%	45%	84
Total	average	485	0.18	219	228	51	45%	47%	85

Figure 24. Comparison of frequency distributions for LS secondary plant throughput rates, 3-month period Nov-05 to Jan-06.

3M Secondary Circuit: Monitoring results for the 3M secondary circuit (see Table 19) suggest on average the utilization is only 78%, or 22% of the time the crusher is not doing useful work. This discrepancy suggests a similar problem to that observed in the LS secondary, where the crusher is idle for periods of time whilst the feed bin level rises into an acceptable operating range for the crusher feed belt to start.

Table 19. Production Totals for 3M Secondary Crushing.

Total 3M Tonnes	3M Hrs Run/Day	3M Hrs Crushed/Day	Difference Run-Crushed
216,952	6.55	5.13	22%

The production rate information in Table 20 shows the plant throughput, power consumption and crusher feed rate. Figure 25 shows the variation in daily production rates over the 3-month period. The results show a much tighter operating range than observed in the LS plant, with a significantly higher average daily throughput (667 vs 485 tph). The fact that the 3M crusher typically operates with a 51 mm gap compared to 44 mm in the LS crusher would probably explain the lower specific power consumption in the 3M plant (0.17 vs. 0.18 kWh/t). Hence the reduced duty in the 3M plant is more significant than the hardness differential of the 3M and LS rock types. On average the crusher recycle load is 50%, which means around half of the incoming feed is coarser than 100 mm (the screen deck aperture).

Table 20. Production Rates for 3M Secondary Crushing.

Month	Values	3M tph	3M kWh/t	6B tph	Crusher Recycle Load%	Crusher Power kW
Nov	average	606	0.17	315	52%	103
Dec	average	658	0.19	329	50%	128
Jan	average	738	0.15	355	48%	113
Total	average	667	0.17	334	50%	114

The histogram chart for the frequency distributions of the daily throughput shown in Figure 25 suggests that very rarely will the 3M plant be fed less than 450 tph, and it often sees throughputs close to 900 tph. Clearly minus any downstream restrictions like the Bivitec screen, and only having to reduce the feed to less than 100 mm, the 3M plant is able to easily attain higher overall throughputs than the LS plant.

Figure 25. Comparison of frequency distributions for 3M secondary plant throughput rates, 3-month period Nov-05 to Jan-06.

Luck Stone Tertiary Circuit: Monitoring results for the tertiary circuit (Table 21) suggest that on average the crusher recycle load is 37%, with 22% of the feed reporting to the dust pile. In terms of overall production, the outgoing products account for only 90% of the feed tons, which again points to the discrepancy between the feed and product weightometers. The major product during the 3-month period was #57.

The production rate information in Table 22 shows the plant throughput, power consumption and all the product rates. This information suggests the plant feedrate is fairly narrowly distributed around an average of 148 tph, with a corresponding specific

power consumption of 0.92 kWh/t. This figure, as noted earlier, represents over 60% of the overall energy consumption at Pittsboro. The 3-month data also highlights the weightometer discrepancy of around 13%. The daily throughput frequency distribution shown in Figure 26 suggests the plant feed rate is always above 90 tph, and 10% of the time exceeds 180 tph. This would indicate some variation in the feed size to the plant, or perhaps the crusher gap has occasionally increased above the 22 to 25 mm setting.

Table 21. Production Totals for LS Tertiary Crushing.

C17 Tonnes	C19 Tonnes	C20 Tonnes	C23 Tonnes	C24 Tonnes	C26 Tonnes	Hrs Crushed
72,908	26,950	16,063	7,939	35,460	6,243	8.55
100%	37%	22%	11%	49%	9%	

Table 22. Production Rates for LS Tertiary Crushing.

Month	Values	C17 tph	LS kWh/t	LS kW	C19 tph	C20 tph	C22 tph	C23 tph	C24 tph	C26 tph	C22 (cal) tph	Error %	Recycle %
Nov	average	161	0.81	131	64	31	131	37	64	14	115	-12%	40%
Dec	average	141	0.89	125	66	28	114	35	57	11	103	-10%	47%
Jan	average	143	1.06	151	48	35	108	0	78	13	91	-16%	34%
Total	average	148	0.92	136	59	31	118	24	66	13	103	-13%	40%

Figure 26. Comparison of frequency distributions for LS tertiary plant throughput rates, 3-month period Nov-05 to Jan-06.

Pittsboro Site Test Work – Optimization and Alternative Designs

Having successfully modeled the baseline conditions, including blast fragmentation and plant response, the next phase was to investigate ways of reducing the energy consumption through alternative blast designs, looking at both the strategy and variables (explosive type, pattern, collar length etc). After reconciling the likely fragmentation and primary throughput from current practice, the Mine-to-Mill team worked with the Luck Stone drill & blast team to come up with a sustainable and viable set of new guidelines for the 3-month evaluation to follow. These guidelines would be sensitive to both corporate and practical limitations. In terms of current practice, the discussions led to a set of definitions related to the burden/spacing for angled holes and blasting domains that Pittsboro routinely encounter. These were:

1. Fractured 21 and 12 meter benches (lifts 2 and 3)
2. Blocky 21 and 12 meter benches (lifts 2 and 3)

One of the critical discoveries made during these discussions was that in the previous 3 months (Nov-05 to Jan-06), the majority of shots were fired in lift 2 (21 meter benches), whereas in the next 3 months the reverse was expected, with the majority of shots in lift 3 (12 meter benches). In both lifts, most shots are in fractured geology, with less than 15% in blocky massive rock. The change from lift 2 to lift 3 will mean the comparison between the first and second 3-month performance may well be compromised since the rock is generally harder in lift 3. As this is inevitable, Pittsboro operations were asked to keep a log of the times that single source material from lift 2 is being fed to the primary crusher. This should help the MTM team extract information from the logging data on the productivity of lift 2 and lift 3 pre- and post- the new blasting guidelines.

Following the discussion of current practice and strategies, a set of potential modifications were proposed aiming to reduce the amount of +150 mm, especially oversize, while not increasing the percent crusher run (-38 mm) significantly. Three subjective blast domains were defined that will require different designs to achieve the objectives of the project. The guidelines are to be used for all blasts on lifts 2 & 3. The blast designs outlined below are a starting point and it is expected that these will be refined over time as the results are assessed. The shot firer still needs to account for various other practical constraints that are inevitable (e.g., face profile) and these guidelines should be combined with knowledge of the objectives and site-specific experience to determine the final design.

As a general guide Luck Stone needs to:

- Decrease the pattern dimensions to reduce coarse fragmentation, and
- Recognize that heavy ANFO and emulsion explosives will produce more fines than ANFO.

The modifications were designed to deal with the following ore domains/conditions:

1. Fractured 21 and 12 meter benches (lifts 2 and 3) – Wet (4.3 x 4.9 m pattern)
2. Fractured 21 and 12 meter benches (lifts 2 and 3) – Damp (4.0 x 4.6 m pattern)
3. Blocky 21 and 12 meter benches (lifts 2 and 3) – 3.7 x 4.3 m pattern

Table 23 summarizes the key components of the guidelines for the proposed modifications in blasting practice.

Table 23. Proposed Blast Design Guidelines.

Parameter	Fractured		Blocky -	Initiation and Timing
	Wet	Damp		
Burden x Spacing (m)	4.3 x 4.9	4.0 x 4.6	3.7 x 4.3	
Explosive Length				Initiate from corner if possible
Blend/Repump	All	Minimum	All	Increase timing between last rows to help protect free face
ANFO	-	Maximum	-	Consider reducing hole delay to ~350 ms to reduce detonator scatter

The following additional notes apply:

- Continue with current procedure for front row design – nominally 5.5 m toe burden and 3.0 m spacing, but no more than 4.3 m at mid-bench level.
- Any corporate or site-specific policies take precedence over these guidelines, e.g., maximum instantaneous charge weight per delay and total initiation duration.
- Aim for 3.7 m stemming but consider bench conditions as per current practice.
- If hole angles vary within a shot then designed burden is at mid-bench level.
- Record any changes to pattern from these general guidelines.

The guidelines represent a modest increase (2-3%) in powder factor for blocky lift 2, fractured lift 2 (damp) and lift 3 (damp/wet) ore domains, a reduction in powder factor of 11% for the fractured (wet) lift 2 ore, and a significant increase of 28% for the blocky lift 3 domain.

Figure 27 shows the key definitions used in setting up the proposed blast design guidelines for Pittsboro.

Figure 27. Blast design definitions.

The Mine-to-Mill guidelines also extended to Continuous Improvement and Timing issues including:

Continuous Improvement

- Minimize the face burden through incremental steps, especially for blocky rock.
- Increase number of rows where feasible – aim for 5 or 6 rows.
- Review fines through the plant and discuss changes to blast design as necessary.
- Review designs for 3M blasts for optimum productivity.

Sample Timing

Figure 28 shows an example of surface timing with particular note to the following:

- When the front row is closer spaced than the rest of the rows, maintain consistent time between echelons. Any extra holes are “in-fill” and should be timed to initiate between the adjacent holes.
- Longer time between the last rows.
- The chart shows the timing analysis where it can be seen that there are four times when two holes initiate with 8 ms. For example, the red bar is when the two red holes are initiating (blue holes have already fired and green are yet to fire). If this is critical, it is possible to change some times to reduce this while still maintaining regular timing.
- The timing contours are indicated by the colored lines. Note they are straight and regularly spaced.
- The same principals apply if the holes are tied up as a flatter echelon.

Figure 28. Example of surface timing.

The Mine-to-Mill team also suggested that Pittsboro include digital photos of each shot over the next 3 months to record the fragmentation. Similarly, the OpStat database (Luck Stone blasting data base) should be modified to allow the drill & blast crew to record the ore structure (fractured/blocky) and ore type (andesite, dacite, basalt etc). This additional information should help the MTM team in the final review of the change in blasting practice.

Simulations were performed using the expected ROMs from both the current practice (21 m and 12 m, fractured and blocky benches) and modified designs (21 m fractured wet/damp and blocky, and 12 m fractured wet/damp and blocky). Table 24 summarizes the results. A summary of the 3-month monitoring results is included for comparison.

The simulation results suggest the model reflects the typical production well (based on given fractured/blocky and lift 2/3 ratios). The results indicate a potential to improve on the primary and secondary productivity (15% and 6% respectively), with a small flow-on gain in the tertiary feed production. Though the overall energy reduction is small (around 1 - 2%), the benefit at the primary and secondary is 6%. The impact on tertiary

production is slight since the feed is a scalped size interval; no fines or coarse, just the middle sizes which are difficult to alter through blasting and crushing. Since Pittsboro must produce a base to meet NC regulations, they cannot adjust the screens in the secondary plant to send more material to the tertiary plant. Overall, the gains are still significant for a well run quarry that expends nearly 65% of its energy in the tertiary plant alone.

Table 24. Comparison of Monitoring Data on Current Practice with Expected Benefits under New Blast Design Guidelines (simulated values in red).

Energy Consumption (kWh/t)		Monitoring Data		Typical	Modified
Plant		LS	3M	LS	LS
Primary		0.10	0.13	0.09	0.08
Secondary		0.18	0.17	0.17	0.16
Tertiary		0.92		0.93	0.93
TOTAL		1.20	0.30	1.19	1.17
Production Rates		LS	3M	LS	LS
Primary	tph	980	869	1009	1157
	kW	95	116	93	95
Secondary	stph	485	667	485	516
	kW	85	114	81	83
Tertiary	stph	148		147	147
	kW	136		136	136

Note that in the simulations the primary crusher was assumed to run on a daily basis at 80% of rated capacity of a C145 jaw crusher.

CONCLUSION

The blasting and processing plant at Pittsboro has been successfully modeled using JKSimBlast and JKSimPlant simulation packages. The blast model was based on the blast design variables and rock properties. The predicted ROM fragmentation appears in line with image analysis results obtained in the field. The plant models were based on the detailed analysis of comprehensive plant audit data collected at Pittsboro. These models were used to investigate a range of new blast design recommendations aiming to reduce the amount of +150 mm, especially oversize, while not increasing the percent crusher run (-38 mm) significantly.

On the basis of simulations, there is scope to increase the primary and secondary production rates with a small reduction in the overall energy consumption by changing the blast design according to the guidelines drawn up in consultation with Luck Stone. The modified blast designs should increase the primary throughput by 15% and secondary by approximately 6%, with an overall specific energy reduction of around 1%. The resulting base fraction in the ROM is expected to increase by 2% from 36% to 38%. The secondary plant feed size will be finer, resulting in a lower circulating load around

the crusher. Though the net yield to the tertiary plant is expected to reduce on account of the increased base fraction in the ROM, the rate of tertiary feed production will increase. The tertiary plant performance and product yields are not expected to change. The impact of the new ROM fragmentation on the Bivtec will need to be closely monitored, particularly if the secondary feed rate is significantly increased and the feed becomes very fine.

The impact of the changes in ROM size distribution on excavation and productivity will need to be closely monitored in the implementation phase to confirm these results. Similarly the next 3-month monitoring period will be used to assess the impact of the new blast design guidelines on the plant performance.

Finally, with the approval of a no-cost time extension, the project is now on schedule to be completed by September 30, 2006, per the timetable shown in Table 25.

Table 25. Project Timetable Showing Current Project Status.

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Appendix I

Summary of JKMRC Drop Weight Breakage Test Results

JKTech Drop Weight Test Parameters for Crushers and FAG/SAG Mills
Tested by JKTech Pty Ltd

Client:	CSS/Virginia Tech	Test Date:	10-Dec-05
Sample Source:	3M	Tester:	Vanegas/Larbi-Bram
Sample Name:	3M (1960-2)	Job No:	05396

Base Data	t10	Eis	t10	Eis	t10	Eis
	17.9	0.40	14.8	0.25	5.2	0.10
	31.2	1.00	8.5	0.25	3.8	0.10
	47.8	2.50	26.2	1.00	7.2	0.25
	44.8	2.46	23.8	1.00	7.3	0.25
	39.2	2.50	21.1	1.00	5.8	0.25

SAG/FAG MILL PARAMETERS

A:	52.5	b:	0.69	A*b:	36.2	Ta:	0.46
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CRUSHER PARAMETERS

CRUSHER APPEARANCE FUNCTION DATA

t10	t75	t50	t25	t4	t2
10	2.4	3.1	5.1	21.9	50.1
20	4.7	6.2	10.1	43.7	81.2
30	7.2	9.5	15.3	63.3	97.0

POWER DATA

	Mean Size (mm)				
	14.53	20.63	28.89	41.08	57.78
	Ecs (kWh/t)				
	0.43	0.36	0.34	0.28	0.18
10	0.43	0.36	0.34	0.28	0.18
20	0.96	0.80	0.74	0.60	0.44
30	1.63	1.33	1.22	0.96	0.89

DENSITY DATA

Mean	2.83	Std Dev	0.17	Max	3.29	Min	2.23
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COMMENTS

JKTech Drop Weight Test Parameters for Crushers and FAG/SAG Mills
Tested by JKTech Pty Ltd

Client:	CSS - Virginia Tech / DOE	Test Date:	3-Dec-05
Sample Source:	LS	Tester:	AT/RC
Sample Name:	LS (1960-1)	Job No:	05396

Base Data	t10	Eis	t10	Eis	t10	Eis
	19.6	0.40	15.2	0.25	6.4	0.10
	34.7	1.00	12.0	0.25	5.6	0.10
	56.5	2.51	33.3	1.00	9.9	0.25
	50.1	2.50	28.6	1.00	7.9	0.25
	42.7	2.50	22.7	1.00	7.2	0.25

SAG/FAG MILL PARAMETERS			
A:	55.9	b:	0.79
		A*b:	44.2
		Ta:	0.35

CRUSHER PARAMETERS

CRUSHER APPEARANCE FUNCTION DATA

t10	t75	t50	t25	t4	t2
10	2.2	2.9	4.8	23.9	56.7
20	4.5	6.0	9.8	45.1	86.3
30	6.9	9.3	15.2	63.2	97.3

POWER DATA

t10	Mean Size (mm)				
	14.53	20.63	28.89	41.08	57.78
t10	Ecs (kWh/t)				
	0.37	0.30	0.25	0.20	0.16
10	0.37	0.30	0.25	0.20	0.16
20	0.83	0.66	0.53	0.45	0.40
30	1.42	1.10	0.88	0.79	0.79

DENSITY DATA

Mean	2.79	Std Dev	0.13	Max	3.12	Min	2.62
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COMMENTS

The Ecs value for 57.78 mm particles at t10 = 30 is doubtful. The value from the next finest particle size has been substituted.

JKTech Drop Weight Test Parameters for Crushers and FAG/SAG Mills
Tested by JKTech Pty Ltd

Client:	CSS	Test Date:	13-Dec-05
Sample Source:	Virginia Tech / Dept of Energy	Tester:	LK
Sample Name:	Basalt (1960-3)	Job No:	05396

Base Data	t10	Eis	t10	Eis	t10	Eis
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00
	53.8	2.50	32.1	1.00	10.2	0.25
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00

SAG/FAG MILL PARAMETERS			
A:	66.3	b:	0.66
		A*b:	43.8
		Ta:	0.80

CRUSHER PARAMETERS

CRUSHER APPEARANCE FUNCTION DATA

t10	t75	t50	t25	t4	t2
10	2.7	3.2	4.8	26.3	49.1
20	4.4	5.7	9.4	47.9	80.5
30	6.0	8.3	14.4	65.3	97.4

POWER DATA

	Mean Size (mm)				
	14.53	20.63	28.89	41.08	57.78
t10	Ecs (kWh/t)				
10	0.00	0.00	0.25	0.00	0.00
20	0.00	0.00	0.54	0.00	0.00
30	0.00	0.00	0.91	0.00	0.00

DENSITY DATA

Mean	#DIV/0!	Std Dev	#DIV/0!	Max	#DIV/0!	Min	#DIV/0!
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COMMENTS

JKTech Drop Weight Test Parameters for Crushers and FAG/SAG Mills
Tested by JKTech Pty Ltd

Client:	CSS	Test Date:	13-Dec-05
Sample Source:	Virginia Tech / Dept of Energy	Tester:	LK
Sample Name:	Dacite (1960-4)	Job No:	05396

Base Data	t10	Eis	t10	Eis	t10	Eis
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00
	55.2	2.50	23.2	1.00	7.6	0.25
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00

SAG/FAG MILL PARAMETERS

A:	100.0	b:	0.30	A*b:	30.0	Ta:	0.80
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CRUSHER PARAMETERS

CRUSHER APPEARANCE FUNCTION DATA

t10	t75	t50	t25	t4	t2
10	2.6	3.2	5.0	22.7	48.8
20	4.1	5.6	9.7	42.9	80.0
30	5.6	8.0	14.4	60.3	97.0

POWER DATA

	Mean Size (mm)				
	14.53	20.63	28.89	41.08	57.78
t10	Ecs (kWh/t)				
10	0.00	0.00	0.36	0.00	0.00
20	0.00	0.00	0.75	0.00	0.00
30	0.00	0.00	1.21	0.00	0.00

DENSITY DATA

Mean	#DIV/0!	Std Dev	#DIV/0!	Max	#DIV/0!	Min	#DIV/0!
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COMMENTS

JKTech Drop Weight Test Parameters for Crushers and FAG/SAG Mills
Tested by JKTech Pty Ltd

Client:	CSS	Test Date:	13-Dec-05
Sample Source:	Virginia Tech / Dept of Energy	Tester:	LK
Sample Name:	Tufts (1960-6)	Job No:	05396

Base Data	t10	Eis	t10	Eis	t10	Eis
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00
	54.9	2.51	30.4	1.00	7.1	0.25
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00

SAG/FAG MILL PARAMETERS			
A:	92.3	b:	0.37
		A*b:	34.2
		Ta:	0.80

CRUSHER PARAMETERS

CRUSHER APPEARANCE FUNCTION DATA

t10	t75	t50	t25	t4	t2
10	2.8	3.2	4.7	25.3	51.5
20	4.3	5.6	9.2	46.7	83.8
30	5.8	8.1	14.1	64.6	100.0

POWER DATA

	Mean Size (mm)				
	14.53	20.63	28.89	41.08	57.78
t10	Ecs (kWh/t)				
10	0.00	0.00	0.31	0.00	0.00
20	0.00	0.00	0.66	0.00	0.00
30	0.00	0.00	1.07	0.00	0.00

DENSITY DATA

Mean	#DIV/0!	Std Dev	#DIV/0!	Max	#DIV/0!	Min	#DIV/0!
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COMMENTS

JKTech Drop Weight Test Parameters for Crushers and FAG/SAG Mills
Tested by JKTech Pty Ltd

Client:	CSS	Test Date:	13-Dec-05
Sample Source:	Virginia Tech / Dept of Energy	Tester:	LK
Sample Name:	Weathered (1960-7)	Job No:	05396

Base Data	t10	Eis	t10	Eis	t10	Eis
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00
	51.6	2.50	38.7	1.00	13.3	0.25
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00

SAG/FAG MILL PARAMETERS

A:	55.2	b:	1.15	A*b:	63.5	Ta:
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CRUSHER PARAMETERS

CRUSHER APPEARANCE FUNCTION DATA

t10	t75	t50	t25	t4	t2
10	3.1	3.5	5.0	22.1	49.9
20	5.1	6.3	9.9	41.9	81.0
30	6.9	9.2	15.2	59.2	97.2

POWER DATA

Mean Size (mm)					
	14.53	20.63	28.89	41.08	57.78
Ecs (kWh/t)					
t10					
10	0.00	0.00	0.17	0.00	0.00
20	0.00	0.00	0.39	0.00	0.00
30	0.00	0.00	0.68	0.00	0.00

DENSITY DATA

Mean	#DIV/0!	Std Dev	#DIV/0!	Max	#DIV/0!	Min	#DIV/0!
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COMMENTS

JKTech Drop Weight Test Parameters for Crushers and FAG/SAG Mills
Tested by JKTech Pty Ltd

Client:	CSS	Test Date:	13-Dec-05
Sample Source:	Virginia Tech / Dept of Energy	Tester:	LK
Sample Name:	Misc (1960-5)	Job No:	05396

Base Data	t10	Eis	t10	Eis	t10	Eis
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00
	53.9	2.50	30.6	1.00	9.5	0.25
	0.0	0.00	0.0	0.00	0.0	0.00
	0.0	0.00	0.0	0.00	0.0	0.00

SAG/FAG MILL PARAMETERS			
A:	71.2	b:	0.56
		A*b:	39.9
		Ta:	0.80

CRUSHER PARAMETERS

CRUSHER APPEARANCE FUNCTION DATA

t10	t75	t50	t25	t4	t2
10	2.8	3.3	4.9	24.0	53.8
20	4.6	5.9	9.6	44.9	86.6
30	6.3	8.6	14.6	62.6	100.0

POWER DATA

	Mean Size (mm)				
	14.53	20.63	28.89	41.08	57.78
t10	Ecs (kWh/t)				
10	0.00	0.00	0.27	0.00	0.00
20	0.00	0.00	0.58	0.00	0.00
30	0.00	0.00	0.97	0.00	0.00

DENSITY DATA

Mean	#DIV/0!	Std Dev	#DIV/0!	Max	#DIV/0!	Min	#DIV/0!
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COMMENTS

Appendix II

Summary of Crusher Settings and Sampling Details

Summary of Crusher Settings and Sampling Details - 12Aug-17Aug'05

Plant	Crusher	Run	OSS (inch)	CSS (inch)	STPH PLC (ave)	Sampling Information	
						Belt Cut Lengths (feet)	
						Coarse	Fine
Primary							
12/08/2005, 9:13am						C2	C2
Nordberg C145 Jaw						36	16.125
12/08/2005, 10:25am						C2	C2
Nordberg C145 Jaw						28	12
Secondary							
15-Aug-05, 9:30-17:00)						C9	
Nordberg G-Cone						24	12
Nordberg G-Cone						16	12
Nordberg G-Cone						12	12
Nordberg G-Cone						16	12
16-Aug-05, 8:00-13:00)						15.83	12
Nordberg G-Cone						12	12
Nordberg G-Cone						24	12
Nordberg G-Cone						19.833	12
Nordberg G-Cone						330 fpm	438 fpm
manual feeder, 25%						C12 fpm (just before belt stopped)	
auto feeder						~114	
auto feeder						205	
auto feeder						205	
auto feeder						191	
auto feeder						205	
auto feeder						208	
manual feeder, 25%						114	
Tertiary							
17-Aug-05, 9:30-12:00)						C17	
Setup #: 6778A						C17	C18
10:00						Feed	Cr Prod
11:10						12	4
12:10						12	4
auto belt speed						106.0	
auto belt speed						137.6	
auto belt speed						165.5	

Appendix III

Audit Sizing Results

Primary Section – Luck Stone Audit

size (mm)	Cum % Passing
300.0	100.00
212.0	99.08
175.0	96.04
150.0	90.49
125.0	83.79
105.0	76.96
90.0	73.04
75.0	66.99
63.5	60.38
50.8	53.44
38.1	46.18
25.4	36.95
19.1	31.13
12.7	24.07
9.5	20.30
6.4	15.84
4.75	13.47
3.35	11.26
2.36	9.20
1.70	7.47
1.18	5.94
0.850	4.74
0.600	3.75
0.425	3.06
0.300	2.36
0.212	1.80
0.150	1.38
0.106	0.99
0.075	0.63

Primary Section – 3M Audit

size (mm)	Cum % Passing
300.0	100.00
212.0	98.82
175.0	90.34
150.0	79.56
125.0	70.63
105.0	63.00
90.0	58.83
75.0	52.68
63.5	47.08
50.8	40.97
38.1	34.49
25.4	28.51
19.1	24.42
12.7	19.30
9.5	16.58
6.4	13.27
4.75	11.47
3.35	9.94
2.36	8.55
1.70	7.45
1.18	6.45
0.850	5.68
0.600	5.00
0.425	4.51
0.300	4.00
0.212	3.60
0.150	3.27
0.106	2.97
0.075	2.71

Secondary Section – Audit 1

C 9-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	95.91
150.0	95.26
125.0	92.93
105.0	90.43
90.0	86.58
75.0	83.63
63.5	80.17
50.8	75.65
38.1	68.77
25.4	57.19
19.1	48.05
12.7	37.19
9.5	31.72
6.4	24.69
4.75	20.97
3.35	17.70
2.36	15.09
1.70	12.97
1.18	11.04
0.850	9.69
0.600	8.53
0.425	7.67
0.300	6.83
0.212	6.16
0.150	5.63
0.106	5.13
0.075	4.68

C 12-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	95.62
150.0	88.81
125.0	78.79
105.0	64.50
90.0	49.73
75.0	32.30
63.5	8.27
50.8	3.34
38.1	1.81
25.4	1.05
19.1	0.83
12.7	0.72
9.5	0.66
6.4	0.60
4.75	0.56
3.35	0.53
2.36	0.49
1.70	0.46
1.18	0.42
0.850	0.39
0.600	0.35
0.425	0.32
0.300	0.28
0.212	0.25
0.150	0.22
0.106	0.19
0.075	0.17

C 13-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	98.80
75.0	93.14
63.5	79.28
50.8	60.09
38.1	39.15
25.4	25.29
19.1	19.86
12.7	14.50
9.5	12.15
6.4	9.34
4.75	7.91
3.35	6.67
2.36	5.70
1.70	4.96
1.18	4.27
0.850	3.74
0.600	3.24
0.425	2.84
0.300	2.45
0.212	2.15
0.150	1.91
0.106	1.71
0.075	1.52

C 14C-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	96.21
19.1	84.16
12.7	51.07
9.5	30.65
6.4	10.63
4.75	7.11
3.35	6.31
2.36	6.14
1.70	6.09
1.18	6.02
0.850	5.95
0.600	5.85
0.425	5.73
0.300	5.51
0.212	5.22
0.150	4.90
0.106	4.54
0.075	4.15

C 16-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	98.13
63.5	86.74
50.8	65.85
38.1	38.53
25.4	9.66
19.1	3.36
12.7	2.29
9.5	2.14
6.4	1.97
4.75	1.89
3.35	1.82
2.36	1.76
1.70	1.71
1.18	1.64
0.850	1.58
0.600	1.50
0.425	1.42
0.300	1.31
0.212	1.20
0.150	1.10
0.106	1.00
0.075	0.91

C 29-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	95.26
19.1	84.38
12.7	64.32
9.5	54.28
6.4	41.13
4.75	34.26
3.35	28.78
2.36	24.31
1.70	20.66
1.18	17.46
0.850	15.12
0.600	13.11
0.425	11.63
0.300	10.22
0.212	9.14
0.150	8.29
0.106	7.52
0.075	6.80

C 30-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	84.08
19.1	27.30
12.7	2.46
9.5	2.26
6.4	2.19
4.75	2.15
3.35	2.12
2.36	2.09
1.70	2.06
1.18	2.03
0.850	1.99
0.600	1.94
0.425	1.88
0.300	1.79
0.212	1.68
0.150	1.57
0.106	1.44
0.075	1.32

C 31-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	100.00
9.5	99.81
6.4	92.93
4.75	79.38
3.35	68.81
2.36	57.00
1.70	47.64
1.18	39.37
0.850	33.48
0.600	28.50
0.425	24.91
0.300	21.61
0.212	19.25
0.150	17.51
0.106	15.97
0.075	14.55

Secondary Section – Audit 2

C 9-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	97.10
150.0	93.88
125.0	92.09
105.0	90.29
90.0	87.38
75.0	82.42
63.5	78.98
50.8	71.88
38.1	64.51
25.4	54.45
19.1	49.05
12.7	39.86
9.5	34.99
6.4	28.43
4.75	24.64
3.35	21.21
2.36	18.31
1.70	15.81
1.18	13.51
0.850	11.87
0.600	10.42
0.425	9.34
0.300	8.28
0.212	7.43
0.150	6.76
0.106	6.13
0.075	5.56

C 12-2

size (mm)	Cum % Passing
300.0	100.00
212.0	96.12
175.0	85.39
150.0	74.91
125.0	67.67
105.0	53.92
90.0	39.11
75.0	20.10
63.5	5.73
50.8	2.56
38.1	1.41
25.4	1.00
19.1	0.82
12.7	0.68
9.5	0.63
6.4	0.56
4.75	0.52
3.35	0.48
2.36	0.44
1.70	0.41
1.18	0.37
0.850	0.34
0.600	0.30
0.425	0.27
0.300	0.24
0.212	0.21
0.150	0.19
0.106	0.17
0.075	0.15

C 13-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	99.73
75.0	99.08
63.5	96.46
50.8	82.81
38.1	59.68
25.4	39.36
19.1	31.30
12.7	23.29
9.5	19.69
6.4	15.31
4.75	13.02
3.35	10.75
2.36	9.11
1.70	7.75
1.18	6.52
0.850	5.66
0.600	4.90
0.425	4.34
0.300	3.79
0.212	3.36
0.150	3.03
0.106	2.74
0.075	2.49

C 14C-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	97.15
19.1	87.27
12.7	70.16
9.5	60.27
6.4	48.23
4.75	41.54
3.35	36.02
2.36	30.81
1.70	26.61
1.18	22.78
0.850	19.82
0.600	17.40
0.425	15.75
0.300	14.12
0.212	12.82
0.150	11.88
0.106	10.98
0.075	10.13

C 16-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	99.53
63.5	90.84
50.8	69.66
38.1	35.56
25.4	7.40
19.1	2.97
12.7	2.25
9.5	2.12
6.4	2.00
4.75	1.94
3.35	1.88
2.36	1.82
1.70	1.77
1.18	1.69
0.850	1.62
0.600	1.54
0.425	1.46
0.300	1.36
0.212	1.26
0.150	1.17
0.106	1.07
0.075	0.98

Secondary Section – Audit 3

C 9-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	95.46
150.0	94.33
125.0	91.89
105.0	88.77
90.0	87.09
75.0	81.28
63.5	78.56
50.8	73.34
38.1	64.25
25.4	53.42
19.1	45.92
12.7	36.21
9.5	31.18
6.4	24.58
4.75	21.03
3.35	17.84
2.36	15.34
1.70	13.37
1.18	11.48
0.850	10.09
0.600	8.87
0.425	7.96
0.300	7.08
0.212	6.38
0.150	5.82
0.106	5.32
0.075	4.86

C 12-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	92.83
150.0	85.71
125.0	79.98
105.0	63.84
90.0	45.26
75.0	27.21
63.5	6.58
50.8	1.68
38.1	1.22
25.4	0.79
19.1	0.69
12.7	0.58
9.5	0.54
6.4	0.47
4.75	0.44
3.35	0.40
2.36	0.37
1.70	0.34
1.18	0.30
0.850	0.27
0.600	0.24
0.425	0.21
0.300	0.18
0.212	0.16
0.150	0.14
0.106	0.12
0.075	0.11

C 13-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	98.16
63.5	91.53
50.8	73.31
38.1	51.96
25.4	36.78
19.1	28.50
12.7	21.23
9.5	17.85
6.4	13.84
4.75	11.74
3.35	9.76
2.36	8.26
1.70	7.03
1.18	5.87
0.850	5.04
0.600	4.30
0.425	3.72
0.300	3.16
0.212	2.72
0.150	2.37
0.106	2.07
0.075	1.81

C 14C-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	97.28
19.1	87.18
12.7	68.10
9.5	58.85
6.4	46.79
4.75	40.09
3.35	34.47
2.36	29.59
1.70	25.61
1.18	22.06
0.850	19.31
0.600	17.04
0.425	15.52
0.300	13.96
0.212	12.69
0.150	11.77
0.106	10.91
0.075	10.14

C 16-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	97.46
63.5	85.48
50.8	59.18
38.1	31.55
25.4	7.32
19.1	3.18
12.7	2.43
9.5	2.30
6.4	2.18
4.75	2.11
3.35	2.04
2.36	1.98
1.70	1.92
1.18	1.85
0.850	1.77
0.600	1.68
0.425	1.59
0.300	1.47
0.212	1.36
0.150	1.25
0.106	1.14
0.075	1.04

Secondary Section – Audit 4

C 9-4

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	95.68
125.0	93.39
105.0	89.77
90.0	85.34
75.0	81.21
63.5	77.15
50.8	71.80
38.1	64.62
25.4	54.39
19.1	47.16
12.7	37.58
9.5	32.47
6.4	25.78
4.75	22.14
3.35	18.93
2.36	16.11
1.70	13.98
1.18	11.98
0.850	10.48
0.600	9.17
0.425	8.18
0.300	7.21
0.212	6.44
0.150	5.83
0.106	5.26
0.075	4.75

C 12-4

size (mm)	Cum % Passing
300.0	100.00
212.0	88.61
175.0	81.53
150.0	73.69
125.0	67.46
105.0	52.03
90.0	40.51
75.0	25.08
63.5	6.75
50.8	3.08
38.1	1.82
25.4	1.09
19.1	0.87
12.7	0.71
9.5	0.65
6.4	0.57
4.75	0.53
3.35	0.49
2.36	0.45
1.70	0.41
1.18	0.37
0.850	0.33
0.600	0.29
0.425	0.26
0.300	0.22
0.212	0.19
0.150	0.17
0.106	0.15
0.075	0.13

C 13-4

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	99.10
63.5	97.97
50.8	92.88
38.1	74.89
25.4	50.82
19.1	40.28
12.7	29.67
9.5	24.99
6.4	19.26
4.75	16.24
3.35	13.46
2.36	11.22
1.70	9.47
1.18	7.85
0.850	6.68
0.600	5.66
0.425	4.89
0.300	4.15
0.212	3.58
0.150	3.13
0.106	2.74
0.075	2.41

C 14C-4

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	96.11
19.1	83.66
12.7	66.28
9.5	56.83
6.4	44.61
4.75	37.95
3.35	32.89
2.36	28.28
1.70	24.56
1.18	21.13
0.850	18.52
0.600	16.33
0.425	14.79
0.300	13.21
0.212	11.97
0.150	10.97
0.106	10.05
0.075	9.21

C 16-4

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	94.00
50.8	74.67
38.1	41.89
25.4	8.90
19.1	3.50
12.7	2.55
9.5	2.40
6.4	2.25
4.75	2.18
3.35	2.12
2.36	2.05
1.70	1.99
1.18	1.91
0.850	1.83
0.600	1.73
0.425	1.63
0.300	1.49
0.212	1.35
0.150	1.23
0.106	1.10
0.075	0.98

Secondary Section – Audit 5

C 9-5

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	98.89
125.0	95.95
105.0	93.61
90.0	93.18
75.0	91.08
63.5	86.41
50.8	79.89
38.1	72.35
25.4	61.85
19.1	54.19
12.7	44.28
9.5	38.93
6.4	31.21
4.75	26.93
3.35	22.90
2.36	19.49
1.70	16.88
1.18	14.37
0.850	12.55
0.600	10.94
0.425	9.74
0.300	8.57
0.212	7.65
0.150	6.93
0.106	6.27
0.075	5.66

C 12-5

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	98.01
150.0	92.22
125.0	84.98
105.0	68.97
90.0	53.35
75.0	30.72
63.5	7.09
50.8	2.68
38.1	1.71
25.4	1.15
19.1	0.89
12.7	0.69
9.5	0.62
6.4	0.55
4.75	0.50
3.35	0.46
2.36	0.41
1.70	0.38
1.18	0.34
0.850	0.30
0.600	0.27
0.425	0.24
0.300	0.21
0.212	0.18
0.150	0.16
0.106	0.14
0.075	0.12

C 13-5

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	99.67
63.5	96.10
50.8	83.34
38.1	60.18
25.4	40.05
19.1	31.71
12.7	23.47
9.5	19.94
6.4	15.57
4.75	13.30
3.35	11.13
2.36	9.42
1.70	8.05
1.18	6.80
0.850	5.88
0.600	5.07
0.425	4.45
0.300	3.85
0.212	3.37
0.150	3.00
0.106	2.67
0.075	2.38

C 14C-5

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	97.50
19.1	87.13
12.7	70.01
9.5	60.86
6.4	48.19
4.75	41.08
3.35	35.33
2.36	30.05
1.70	25.82
1.18	22.05
0.850	19.20
0.600	16.72
0.425	14.95
0.300	13.20
0.212	11.85
0.150	10.80
0.106	9.83
0.075	8.97

C 16-5

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	97.33
63.5	87.62
50.8	65.67
38.1	34.01
25.4	7.01
19.1	2.73
12.7	2.04
9.5	1.91
6.4	1.80
4.75	1.74
3.35	1.67
2.36	1.61
1.70	1.55
1.18	1.48
0.850	1.42
0.600	1.35
0.425	1.28
0.300	1.18
0.212	1.08
0.150	0.98
0.106	0.88
0.075	0.79

Secondary Section – Audit 6

C 9-6

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	94.71
150.0	88.36
125.0	77.32
105.0	70.63
90.0	60.99
75.0	53.26
63.5	46.37
50.8	40.28
38.1	33.30
25.4	25.92
19.1	21.85
12.7	17.27
9.5	15.09
6.4	12.10
4.75	10.44
3.35	9.03
2.36	7.74
1.70	6.71
1.18	5.76
0.850	5.04
0.600	4.40
0.425	3.93
0.300	3.46
0.212	3.09
0.150	2.79
0.106	2.53
0.075	2.28

C 12-6

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	88.52
150.0	73.84
125.0	63.33
105.0	48.15
90.0	35.63
75.0	18.36
63.5	3.48
50.8	2.08
38.1	1.44
25.4	0.96
19.1	0.77
12.7	0.62
9.5	0.54
6.4	0.48
4.75	0.43
3.35	0.39
2.36	0.35
1.70	0.32
1.18	0.29
0.850	0.26
0.600	0.23
0.425	0.21
0.300	0.18
0.212	0.16
0.150	0.15
0.106	0.13
0.075	0.12

C 13-6

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	94.85
63.5	84.99
50.8	63.79
38.1	43.04
25.4	29.81
19.1	23.94
12.7	17.87
9.5	15.11
6.4	11.68
4.75	9.88
3.35	8.26
2.36	6.96
1.70	5.92
1.18	4.95
0.850	4.25
0.600	3.64
0.425	3.17
0.300	2.70
0.212	2.31
0.150	2.01
0.106	1.75
0.075	1.55

C 14C-6

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	95.93
19.1	82.73
12.7	64.80
9.5	55.73
6.4	43.86
4.75	37.33
3.35	32.05
2.36	27.34
1.70	23.43
1.18	19.96
0.850	17.24
0.600	14.91
0.425	13.26
0.300	11.60
0.212	10.32
0.150	9.33
0.106	8.44
0.075	7.67

C 16-6

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	99.40
75.0	95.07
63.5	85.39
50.8	57.55
38.1	28.76
25.4	4.86
19.1	1.89
12.7	1.38
9.5	1.27
6.4	1.17
4.75	1.11
3.35	1.06
2.36	1.01
1.70	0.97
1.18	0.92
0.850	0.87
0.600	0.82
0.425	0.77
0.300	0.71
0.212	0.65
0.150	0.59
0.106	0.53
0.075	0.47

Secondary Section – Audit 7

C 9-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	98.17
150.0	97.34
125.0	94.29
105.0	87.57
90.0	81.25
75.0	74.57
63.5	65.94
50.8	52.17
38.1	38.24
25.4	26.36
19.1	20.60
12.7	14.73
9.5	12.38
6.4	9.37
4.75	7.94
3.35	6.79
2.36	5.83
1.70	5.10
1.18	4.44
0.850	3.97
0.600	3.55
0.425	3.22
0.300	2.90
0.212	2.63
0.150	2.42
0.106	2.22
0.075	2.04

C 12-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	97.31
150.0	81.52
125.0	67.36
105.0	58.14
90.0	44.33
75.0	26.08
63.5	5.53
50.8	3.03
38.1	1.96
25.4	1.18
19.1	0.95
12.7	0.77
9.5	0.68
6.4	0.57
4.75	0.51
3.35	0.45
2.36	0.40
1.70	0.36
1.18	0.32
0.850	0.28
0.600	0.25
0.425	0.22
0.300	0.19
0.212	0.17
0.150	0.15
0.106	0.13
0.075	0.11

C 13-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	98.70
75.0	94.93
63.5	85.98
50.8	66.78
38.1	42.72
25.4	28.62
19.1	22.61
12.7	16.57
9.5	13.86
6.4	10.61
4.75	8.91
3.35	7.36
2.36	6.23
1.70	5.34
1.18	4.52
0.850	3.91
0.600	3.39
0.425	2.96
0.300	2.53
0.212	2.19
0.150	1.93
0.106	1.69
0.075	1.48

C 14C-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	95.24
19.1	80.00
12.7	45.13
9.5	25.59
6.4	6.47
4.75	3.13
3.35	2.67
2.36	2.58
1.70	2.53
1.18	2.47
0.850	2.43
0.600	2.37
0.425	2.32
0.300	2.23
0.212	2.12
0.150	2.01
0.106	1.86
0.075	1.69

C 16-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	98.39
63.5	87.73
50.8	56.27
38.1	28.74
25.4	5.91
19.1	2.36
12.7	1.63
9.5	1.52
6.4	1.36
4.75	1.29
3.35	1.23
2.36	1.18
1.70	1.13
1.18	1.08
0.850	1.03
0.600	0.98
0.425	0.92
0.300	0.85
0.212	0.78
0.150	0.72
0.106	0.65
0.075	0.59

C 29-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	94.73
19.1	77.02
12.7	55.37
9.5	45.80
6.4	34.64
4.75	29.13
3.35	24.73
2.36	21.02
1.70	18.16
1.18	15.57
0.850	13.72
0.600	12.09
0.425	10.84
0.300	9.62
0.212	8.65
0.150	7.88
0.106	7.18
0.075	6.56

C 30-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	79.93
19.1	25.11
12.7	2.48
9.5	2.14
6.4	1.99
4.75	1.95
3.35	1.89
2.36	1.85
1.70	1.81
1.18	1.77
0.850	1.73
0.600	1.68
0.425	1.63
0.300	1.55
0.212	1.47
0.150	1.38
0.106	1.27
0.075	1.16

C 31-7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	100.00
9.5	99.53
6.4	93.67
4.75	81.27
3.35	68.62
2.36	57.18
1.70	48.37
1.18	41.05
0.850	36.01
0.600	31.47
0.425	27.92
0.300	24.36
0.212	21.51
0.150	19.35
0.106	17.44
0.075	15.77

Secondary Section – 3M Audit

C 4

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	89.18
150.0	83.62
125.0	68.47
105.0	54.43
90.0	47.77
75.0	42.26
63.5	38.45
50.8	30.99
38.1	24.22
25.4	17.42
19.1	13.76
12.7	10.06
9.5	8.55
6.4	6.65
4.75	5.68
3.35	4.85
2.36	4.24
1.70	3.76
1.18	3.32
0.850	3.00
0.600	2.70
0.425	2.46
0.300	2.21
0.212	1.99
0.150	1.81
0.106	1.64
0.075	1.47

C 6B

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	99.50
90.0	97.70
75.0	82.27
63.5	79.09
50.8	61.29
38.1	40.35
25.4	27.95
19.1	21.73
12.7	15.95
9.5	13.30
6.4	10.09
4.75	8.44
3.35	6.97
2.36	5.76
1.70	4.82
1.18	4.01
0.850	3.39
0.600	2.88
0.425	2.52
0.300	2.15
0.212	1.85
0.150	1.62
0.106	1.41
0.075	1.22

C 7

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	99.28
75.0	94.16
63.5	86.00
50.8	69.54
38.1	50.15
25.4	36.81
19.1	29.54
12.7	22.16
9.5	18.86
6.4	14.72
4.75	12.56
3.35	10.75
2.36	9.20
1.70	8.01
1.18	6.91
0.850	6.12
0.600	5.42
0.425	4.88
0.300	4.34
0.212	3.90
0.150	3.55
0.106	3.21
0.075	2.90

Tertiary Section – Audit 1

C 17-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	98.70
63.5	93.74
50.8	73.95
38.1	43.34
25.4	17.37
19.1	9.02
12.7	4.99
9.5	4.29
6.4	3.65
4.75	3.39
3.35	3.19
2.36	3.02
1.70	2.86
1.18	2.70
0.850	2.55
0.600	2.40
0.425	2.26
0.300	2.08
0.212	1.90
0.150	1.74
0.106	1.58
0.075	1.43

C 18-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	99.40
25.4	87.61
19.1	50.49
12.7	28.25
9.5	21.91
6.4	15.51
4.75	12.71
3.35	10.48
2.36	8.77
1.70	7.46
1.18	6.33
0.850	5.51
0.600	4.81
0.425	4.31
0.300	3.79
0.212	3.38
0.150	3.04
0.106	2.72
0.075	2.42

C 19-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	99.33
25.4	74.76
19.1	14.26
12.7	1.99
9.5	1.79
6.4	1.66
4.75	1.61
3.35	1.55
2.36	1.51
1.70	1.47
1.18	1.43
0.850	1.40
0.600	1.35
0.425	1.31
0.300	1.25
0.212	1.18
0.150	1.11
0.106	1.03
0.075	0.94

C 20-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	100.00
9.5	100.00
6.4	99.31
4.75	97.33
3.35	90.06
2.36	79.29
1.70	67.10
1.18	55.19
0.850	46.81
0.600	39.51
0.425	33.92
0.300	28.49
0.212	24.27
0.150	21.03
0.106	18.22
0.075	15.83

C 22-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	92.24
12.7	48.06
9.5	30.50
6.4	14.10
4.75	7.56
3.35	3.97
2.36	2.10
1.70	1.57
1.18	1.45
0.850	1.38
0.600	1.32
0.425	1.27
0.300	1.20
0.212	1.13
0.150	1.06
0.106	0.98
0.075	0.88

C 24-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	88.62
12.7	32.78
9.5	12.42
6.4	5.17
4.75	2.60
3.35	1.31
2.36	0.67
1.70	0.51
1.18	0.45
0.850	0.42
0.600	0.39
0.425	0.37
0.300	0.34
0.212	0.32
0.150	0.30
0.106	0.28
0.075	0.25

C 26-1

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	100.00
9.5	93.03
6.4	46.79
4.75	23.27
3.35	9.52
2.36	2.53
1.70	1.00
1.18	0.79
0.850	0.73
0.600	0.67
0.425	0.63
0.300	0.59
0.212	0.55
0.150	0.52
0.106	0.48
0.075	0.44

Tertiary Section – Audit 2

C 17-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	99.60
63.5	93.47
50.8	76.64
38.1	49.29
25.4	20.33
19.1	10.87
12.7	6.03
9.5	5.19
6.4	4.36
4.75	4.03
3.35	3.78
2.36	3.55
1.70	3.36
1.18	3.16
0.850	2.98
0.600	2.78
0.425	2.60
0.300	2.39
0.212	2.18
0.150	1.99
0.106	1.81
0.075	1.62

C 18-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	95.01
19.1	69.57
12.7	41.04
9.5	32.32
6.4	23.36
4.75	19.10
3.35	15.43
2.36	12.67
1.70	10.56
1.18	8.74
0.850	7.43
0.600	6.34
0.425	5.57
0.300	4.81
0.212	4.21
0.150	3.74
0.106	3.31
0.075	2.92

C 19-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	99.72
25.4	86.00
19.1	23.55
12.7	2.57
9.5	2.35
6.4	2.17
4.75	2.08
3.35	2.01
2.36	1.96
1.70	1.91
1.18	1.86
0.850	1.82
0.600	1.76
0.425	1.71
0.300	1.64
0.212	1.56
0.150	1.49
0.106	1.40
0.075	1.30

C 20-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	100.00
9.5	100.00
6.4	99.58
4.75	97.49
3.35	89.05
2.36	77.42
1.70	64.83
1.18	53.04
0.850	44.58
0.600	37.37
0.425	32.00
0.300	26.81
0.212	22.86
0.150	19.87
0.106	17.32
0.075	15.18

C 22-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	95.64
12.7	52.53
9.5	35.55
6.4	17.60
4.75	9.72
3.35	5.06
2.36	2.77
1.70	2.17
1.18	2.02
0.850	1.95
0.600	1.88
0.425	1.81
0.300	1.73
0.212	1.64
0.150	1.56
0.106	1.47
0.075	1.36

C 24-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	93.75
12.7	39.93
9.5	20.27
6.4	7.70
4.75	3.76
3.35	1.72
2.36	0.88
1.70	0.66
1.18	0.60
0.850	0.56
0.600	0.52
0.425	0.49
0.300	0.46
0.212	0.42
0.150	0.39
0.106	0.36
0.075	0.32

C 26-2

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	99.94
9.5	91.25
6.4	51.28
4.75	26.07
3.35	11.33
2.36	3.15
1.70	1.04
1.18	0.74
0.850	0.66
0.600	0.60
0.425	0.56
0.300	0.52
0.212	0.49
0.150	0.46
0.106	0.43
0.075	0.41

Tertiary Section – Audit 3

C 17-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	99.70
63.5	92.13
50.8	75.66
38.1	48.35
25.4	22.20
19.1	12.18
12.7	6.65
9.5	5.66
6.4	4.77
4.75	4.36
3.35	4.06
2.36	3.80
1.70	3.58
1.18	3.35
0.850	3.15
0.600	2.93
0.425	2.74
0.300	2.51
0.212	2.29
0.150	2.09
0.106	1.89
0.075	1.70

C 18-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	99.03
19.1	87.97
12.7	59.16
9.5	47.11
6.4	35.05
4.75	29.15
3.35	24.59
2.36	20.49
1.70	17.39
1.18	14.72
0.850	12.80
0.600	11.16
0.425	9.99
0.300	8.85
0.212	7.98
0.150	7.30
0.106	6.69
0.075	6.17

C 19-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	99.92
25.4	91.37
19.1	37.04
12.7	3.15
9.5	2.79
6.4	2.55
4.75	2.45
3.35	2.39
2.36	2.33
1.70	2.28
1.18	2.22
0.850	2.17
0.600	2.11
0.425	2.04
0.300	1.95
0.212	1.85
0.150	1.75
0.106	1.64
0.075	1.52

C 20-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	100.00
9.5	100.00
6.4	99.70
4.75	97.94
3.35	88.79
2.36	74.78
1.70	60.74
1.18	46.73
0.850	37.07
0.600	29.21
0.425	23.56
0.300	18.29
0.212	14.28
0.150	11.30
0.106	8.70
0.075	6.51

C 22-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	98.37
12.7	58.54
9.5	39.96
6.4	20.35
4.75	11.11
3.35	5.54
2.36	3.01
1.70	2.33
1.18	2.14
0.850	2.05
0.600	1.96
0.425	1.88
0.300	1.78
0.212	1.68
0.150	1.58
0.106	1.46
0.075	1.33

C 24-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	97.87
12.7	48.19
9.5	26.92
6.4	11.89
4.75	5.77
3.35	2.54
2.36	1.14
1.70	0.77
1.18	0.67
0.850	0.62
0.600	0.58
0.425	0.54
0.300	0.50
0.212	0.46
0.150	0.43
0.106	0.39
0.075	0.35

C 26-3

size (mm)	Cum % Passing
300.0	100.00
212.0	100.00
175.0	100.00
150.0	100.00
125.0	100.00
105.0	100.00
90.0	100.00
75.0	100.00
63.5	100.00
50.8	100.00
38.1	100.00
25.4	100.00
19.1	100.00
12.7	99.88
9.5	89.12
6.4	46.61
4.75	23.33
3.35	9.97
2.36	2.98
1.70	1.11
1.18	0.81
0.850	0.74
0.600	0.67
0.425	0.63
0.300	0.59
0.212	0.56
0.150	0.53
0.106	0.51
0.075	0.48

Appendix IV

8605 Blast Design

Blast No.	8605 (4.3 x 3.8 m)
Bench Height (m)	21.0
Burden (m)	4.3
Spacing (m)	3.8
S/B Ratio (Equilateral = 1.15)	0.89
Hole Diameter (mm)	165.1
Subdrill (m)	1.0
Hole Length (m)	22.1
Stemming Height (m)	4.8
Staggered (Y/N)	N
Explosive (Bottom Deck)	Hydromite 4400
Explosive Length (m)	17.3
Density (kg/m³)	1220
VOD (m/s)	5500
RWS	95
Explosive Weight (kg)	452.2
Explosive (Top Deck)	ANFO
Explosive Length (m)	0.0
Density (kg/m³)	850
VOD (m/s)	3962
RWS	100
Explosive Weight (kg)	0.0
Total Explosive Weight (kg)	452.2
Total Charge Length (m)	17.3
Powder Factor (kg/m³)	1.31
Powder Factor (kg/t)	0.45
Domain	Basalt
Rock Density (kg/m³)	2950
Young's Modulus (GPa)	67
UCS (MPa)	200
Mean Insitu Block Size (m)	0.3

Appendix V

JKSimBlast Results

8605 Blast Design

Blast No.	8605 (4.3 x 3.8 m)
Blast Model Size (mm)	Cum % Pass
3000	100.0
2000	100.0
1500	99.9
1000	99.6
750	98.6
500	95.3
300	86.5
200	76.1
150	70.5
100	55.3
70	45.1
40	34.8
31.5	31.1
19.0	24.3
13.2	20.2
9.5	17.0
4.75	11.8
3.35	9.7
2.36	8.0
1.70	6.7
1.18	5.4
20% Passing Size (mm)	12.9
50% Passing Size (mm)	83.3
80% Passing Size (mm)	230.5
Top Size (mm)	1338.9