Blast Optimization of Hard Ores at Phu Kham Open Pit

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Abstract

The Phu Kham Copper-Gold Operation (PKM) is a large-scale open pit mine located in northern Laos. It was developed and is operated by Phu Bia Mining Limited (PBM) a Lao-registered subsidiary company of Australian incorporated, PanAust Limited. Production commenced at Phu Kham in 2008. Since the second half of 2016, there has been a significant increase in ore hardness and this has negatively impacted the PKM concentrator and resulted in lower SAG mill throughput rates. Over the remaining life of mine, the changing ore body and increase in ore hardness is forecast to continue as the pit deepens and the availability of softer blending ores reduce. To manage this risk, PKM initiated a Hard Ores Management Program to determine the most effective way to improve the mill throughput of harder ores. This involved conducting a number of innovative and process control driven blasting trials to optimize run-of-mine (ROM) fragmentation and other blasting outcomes. From 2016 to 2017, the performance of high powder factor blasting, electronic detonators and fast timing, high velocity of detonation (VOD) explosives, double-priming, and deck blasting, were individually and systematically assessed. The success of each blasting trial was then based on a 'value for money' criteria. This criteria is a cost / benefit analysis that weighed-up the additional cost to implement the trial against the measured improvement in mill throughput. Electronic and high VOD 90:10 emulsion:ANFO blasts were determined to have the best value for money, achieving an increase in mill throughput of 54% compared to baseline. This paper discusses how the implementation of an innovative and process control driven blasting trial methodology was able to successfully manage the hard ore challenges at PKM. In addition, this success was achieved without any major cost implications, safety incidents or process plant set-backs.

Introduction

The Phu Kham Copper-Gold Operation (PKM) is a large-scale open pit mine located in northern Laos. Figure 1 shows the location of PKM. The mine was developed and is operated by Phu Bia Mining Limited (PBM) a Lao-registered subsidiary company of Australian incorporated, PanAust Limited. PBM is 90% owned by PanAust with the Government of Laos holding the remaining 10%.

The operating strategy for the Phu Kham mine is focused on delivering safe, high value, low cost and reliable outcomes. PKM consists of a single large pit of 450m (492 yd) depth and is the largest open pit mine in Laos. Total material mined at PKM during 2016 was 57.0 million tonnes (Mt), with 19.1Mt of ore processed (63 Mton, and 21 Mton, respectively). The average copper (Cu) head grade was 0.58%, and gold and silver head grades were 0.28grams/t (g/t) (0.01 oz/ton) and 2.20g/t (0.06 oz/ton) respectively. Copper in concentrate production for the year was 89,187t (98,312 ton) at a C1 cash cost of $1.10/lb Cu. All currency in this paper is in U.S. dollars ($USD) unless otherwise stated.

Figure 1. Phu Kham Copper-Gold Operation on Laos

Since the second half of 2016 there has been a significant increase in ore hardness and this has negatively impacted the PKM concentrator and resulted in lower SAG mill throughput rates. The SAG mill was identified as the primary bottleneck as the higher resistance to impact breakage, and the higher mill residence times required to break harder ores, overload the mill weight and increase the total energy load required for breakage. Primary skarns and diorites form the predominant hard ores and make up approximately 7-8 Mtpa (8-9 Mton) of a total 18-19 Mt (20-21 Mton) milled per year. Over the remaining life of mine, the changing ore body and increasing ore feed hardness is forecast to continue as the pit deepens and the availability of softer blending ores reduce.

To effectively manage this risk, PKM initiated a Hard Ores Management Program to quantify and develop improved plans and tactics leading to improved mill throughput of harder ores. As part of this program a number of innovative and process control driven blasting trials were conducted to individually and systematically assess the performance of:

- High powder factor (PF) blasts
- Electronic detonators (ED) and fast initiation timing
- High velocity of detonation (VOD) / high density explosives
- Double-priming (DP) and deck blasting

The following section discusses the measurements taken in order to establish the baseline blast conditions.

Baseline measurements

Baseline measurements were conducted in order to establish a benchmark to quantify and compare against any improvements in blast outcomes and mill performance gained from future hard ore blasting trials. Baseline blast parameters in PKM hard ore consisted of a bench height of 10 m (32.8 ft), burden 3.5m (11.5 ft), spacing 4.5m (14.8 ft), hole diameter 200 mm (7.87"), 70:30 emulsion:ANFO explosive, PF 1.6 kg/m3 (2.70 lbs/yd3), drill and blast (D&B) unit cost 0.75 \$/t, and drill yield 42.2 t/m (11.7 ton/ft).

Baseline blast trials consisted of measuring the standard of blast implementation QA/QC, high speed video, VOD, heave, movement, fragmentation, and milling performance. Crusher product (CV01) belt cuts were measured for product size distribution (PSD), lithology, density, and hardness (point load test). The baseline dataset consists of 15 x hard ore CV01 belt cuts and 3 x soft ore belt cuts. Soft ore belt cuts were taken to determine the upper limits of fragmentation. Over time, the baseline data set has been added to with belt cuts taken from the subsequent hard ore blasting trials.

Results of the CV01 belt cuts are shown below in Figure 2. In this figure, the results of the baseline trials are shown in blue. Results indicate the SAG mill throughput will increase if the PSD of hard ore presenting to the SAG mill is optimized by:

- Increasing the % fines (<25mm & <10mm, <1.0 inch & <0.40 inch),
- Minimising critical size % (25 – 75mm, 1.0 – 3.0 inch) and,
- Reducing the SAG media % (+100mm, +4.0 inch).

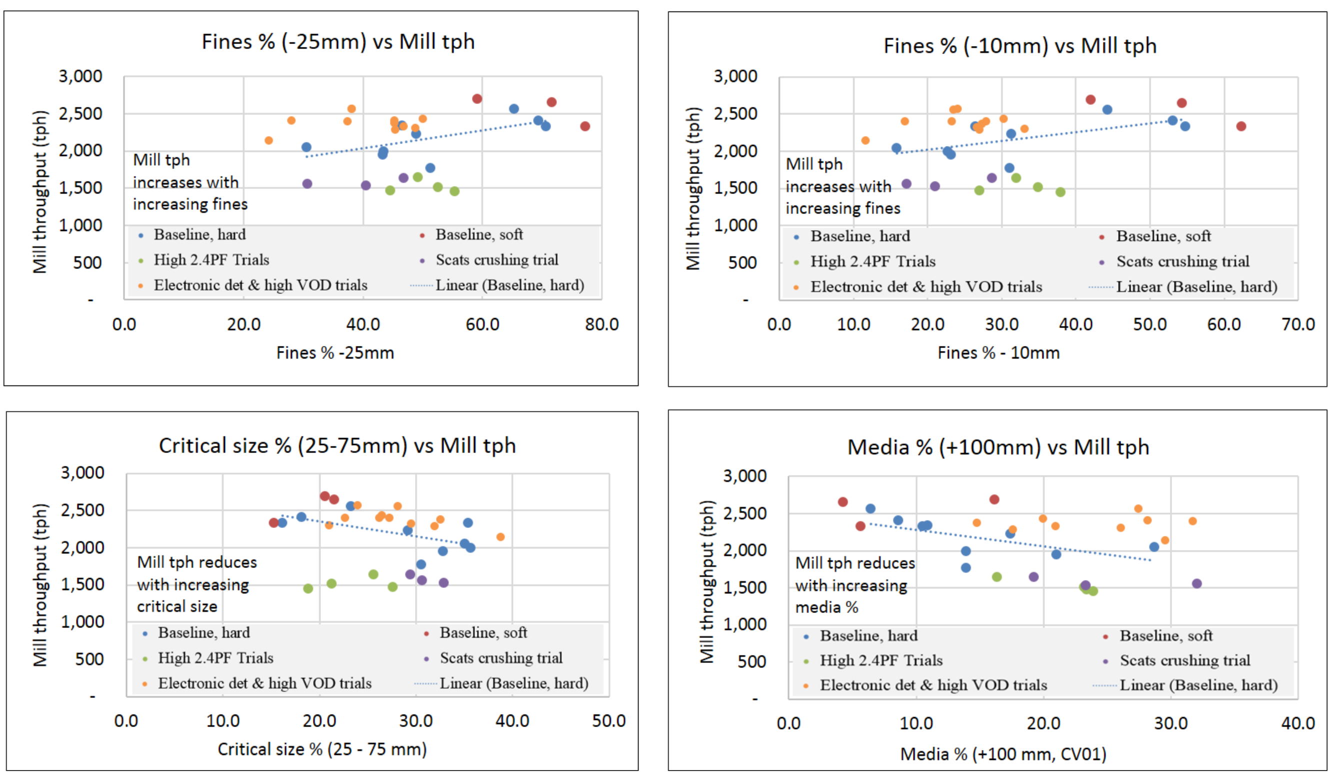


Figure 2. Crusher product (CV01) belt cut trends

Now that the baseline measurements have been explained, the following section will discuss the outcomes of the hard ore blasting trials.

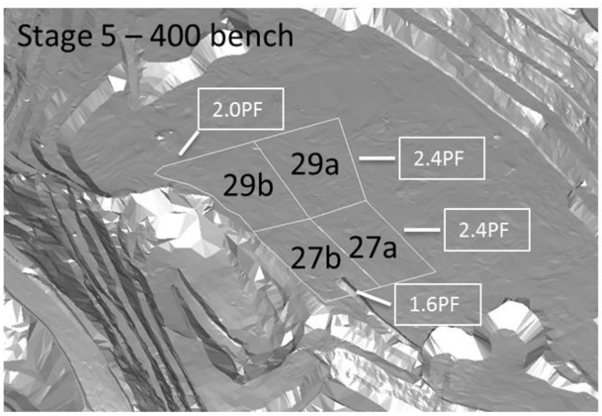
Hard ore blasting trials

The aim of the hard ore blasting trials was to determine the most effective way to improve mill throughput of harder ores. The trials individually and systematically assessed the performance of high powder factor blasting, electronic detonators and fast timing, high velocity of detonation (VOD) blasts, double-priming, and deck blasting. The trials were conducted over a six-month period from 2016 to 2017.

High powder factor blast trials

A number of case studies have clearly demonstrated downstream productivity benefits from increases in blast energy, or powder factor (Kanchibotla, et al., 2015), (Rantapaa, Mckinstry, & Bolles, 2005), and (Scott, Morrell, & Clark, 2002).

In December 2016, PKM and consultants JKTech conducted high powder factor blast trials aimed at improving mill throughput of harder ores, primarily by increasing the percentage of fines in ROM PSD. The trial consisted of 4 blasts with a 70:30 emulsion:ANFO explosive and various powder factors: 1 x 1.6kg/m3 (2.70 lbs/yd3) PF baseline, 1 x 2.0kg/m3 (3.37 lbs/yd3) PF, and 2 x 2.4kg/m3 (4.05 lbs/yd3) PF. The blast were conducted alongside each other in the hard ore zone on the 400RL bench, Stage 5 central pit. The design parameters and blast layouts are shown in Figure 3. The 2 x 2.4PF blasts were single-sourced through the mill for 4 – 6 hours and the mill performance measured.



Blast Design	Baseline 1.6 PF	High 2.0 PF	High 2.4 PF
Bench height m	10	10	10
Burden m	3.5	3.3	3.0
Spacing m	4.5	3.8	3.5
Hole diameter mm	200	200	200
Stemming length m	4	4	4
Explosive			
Product	Em. blend 70:30	Em. blend 70:30	Em. blend 70:30
Powder Factor (kg/m3)	1.6	2.0	2.4
Costs			
Total D&B $/t	0.75	0.94	1.12
Drill Yield t/m drilled	42.2	32.6	28.1

Figure 3. PKM high powder factor blast trials setup

The next section of the paper will discuss the results of the electronic detonator (ED) and fast initiation timing blast trials, double-priming, high VOD, and decking blast trials. The subsequent sections of the paper will compare and discuss the fragmentation and mill performance results of all blast trials.

Electronic detonator blast trials

Electronic detonator trials were conducted at PKM in early 2017. This was the first time for electronic detonators to be been trialled at PBM and involved bringing in external consultants from PBM's explosive suppliers Austin Powder and TKPV. The focus of the trials was on fragmentation and the potential to generate a finer and more uniform ROM PSD by improving blast timing control, explosive energy distribution, and shock/stress wave interaction. The trials also assessed the ability to reduce workload, simplify logistics, improve wall control, grade control, and reduce costs and energy duty on downstream processing. Various case studies have in the past demonstrated these benefits of electronic detonators (McFerren & Moodley, 2004), (Grobler, 2003), and (Deacon, Duniam, & Jones, 1997).

The trial consisted of 5 blasts in the hard ore zone on the 380RL bench, stage 5 central pit. The layout of the blasts and the CV01 belt cut taking process is shown in Figure 4. The blast parameters are given in Table 1. The trials involved assessing the performance of electronic detonators using the baseline blasting conditions (PF 1.6 kg/m3, 2.70 lbs/yd3, 70:30 emulsion:ANFO explosive), as well as with the use of faster timing, double-priming, higher velocity of detonation (VOD) / high density explosives, and deck blasting.

The electronic detonator and faster timing trials were aimed at maximizing the interaction of inter-hole shock / stress waves to increase fragmentation with the same amount of explosive energy. The double-priming trial was designed to assess the theory of improved breakage at the intersection of detonation fronts in the blast column and whether this translated into a measured increase in fines generation. The high VOD explosive trial was aimed at producing greater shock energy in the blast to increase the potential for fines generation. Another theorized effect of high VOD explosives has been the proposed reduction in inherent strength of the blasted rock fragments. This effect has been termed 'micro-cracking' (Neilsen & Malvik, 1999) or 'preconditioning' (Michaux & Djordjevic, 2005).

Figure 4. PKM electronic blast trials setup & CV01 belt cut

Table 1. Electronic detonator (ED) blast design parameters

Blast	**380-19a**	**380-19b**	**380-16a**	**380-16b**	**380-16c**
Burden	3.5m (11.5 ft)	3.5m (11.5 ft)	3.5m (11.5 ft)	3.9m (12.8 ft)	3.8m (12.5 ft)
Spacing	4.5m (14.8 ft)	4.5m (14.8 ft)	4.5m (14.8 ft)	4.5m (14.8 ft)	4.5m (14.8 ft)
Explosive					
Em:ANFO %	70:30	70:30	70:30	100:0	90:10
Density (g/cc)	1.15	1.15	1.15	1.28	1.25
VOD (m/sec)	5200 – 5500	5200 – 5500	5200 – 5500	5600 – 6000	5600 – 6000
Initiation (ED)					
No. of primers	Single (SP)	Double (DP)	Single (SP)	Single (SP)	Single (SP)
IH& IR (ms)	9 ms & 30 ms	9 ms & 30 ms	4 ms & 15 ms	4 ms & 15 ms	9 ms & 30 ms
Costs					
D&B unit cost	0.79 $/t	0.80 $/t	0.79 $/t	0.78 $/t	0.78 $/t
Drill yield (t/m)	42 (12 ton/ft)	42 (12 ton/ft)	42 (12 ton/ft)	47 (13 t/ft)	46 (13 t/ft)

A powder factor of 1.6 kg/m3 (2.70 lbs/yd3) was maintained for all electronic blasts in order to quantify and attribute any potential improvements in fragmentation and mill throughput, back to either the use of electronic detonators and/or the use of higher VOD explosives.

Rather than conducting a full 4-6 hour mill trial on each blast, it was instead decided to measure CV01 belt cuts from each of the first 4 blasts (380-19a, 19b, 16a, and 16b). Then, based on the CV01 belt cuts, a final optimized blast (380-16c) was designed with parameters that would most likely increase fines %, minimize critical size %, and reduce SAG media. A full 4-6 hour mill trial was then conducted this blast.

Of the first 4 blasts (380-19a, 19b, 16a, and 16b), the high VOD and high density 100% emulsion blast (16b) produced the most fines in the CV01 belt cuts. This was likely caused by an increase in shock energy and crushed zone surrounding the blast hole. The final optimized ED blast (380-16c) was designed with a PF of 1.6 kg/m3 (2.70 lbs/yd3), high VOD 90:10 emulsion:ANFO explosive, 9ms inter-hole and 30ms inter-row timing. A 90:10 emulsion:ANFO was used in order to gain the benefits of higher VOD, but to also add a bit of gas energy to promote more movement and create an easier muck pile to dig.

Fragmentation results

Split desktop image analysis software was used to measure ROM blast fragmentation of the baseline blasts, high powder factor blasts, and the electronic and high VOD blast (380-16c). The results are shown below in Table 2. Results show the high PF blasts produced, on average, the lowest blast P80 (mm). The electronic detonator and high VOD blast produced the largest top size (mm).

Table 2. ROM blast fragmentation of all blast trials

Blast Trial	**Baseline**	**High Energy 2.4PF**	**Electronic & high VOD**
Details	70:30Em, NONEL,1.6PF	70:30Em, NONEL,2.4PF	90:10 Em, Elec, 1.6 PF
Top size, mean	630 mm (24.8”)	670 mm (26.4”)	915 mm (36.0”)
P80, mean	157 mm (6.18”)	144 mm (5.67”)	246 mm (9.68”)
Blast count (#)	32	2	1

To quantify the amount of fines generated in the blast, CV01 belt cuts were measured. Results of the baseline blasts, high powder factor blasts, and the electronic and high VOD blast are shown in Table 3.

Table 3. Crusher product CV01 belt cuts of all blast trials

Blast Trial	**Baseline**	**High Energy 2.4PF**	**Electronic & high VOD**
Details	70:30Em,NONEL, 1.6PF	70:30Em,NONEL, 2.4PF	90:10 Em, Elec, 1.6 PF
No. of samples	15	4	2
Fines % (-10 mm, 0.4”), mean	26.1 %	32.9 %	26.9 %
Fines % (-25 mm, 1”), mean	44.7 %	50.4 %	45.4 %
Critical size% (25 –75mm, 0.1-3”)	31.7 %	23.3 %	31.9 %
Media % (+100 mm, 3.9”)	18.7 %	21.7 %	17.6 %

Results in Table 3 show the high PF blasts produced, on average, the most amount of fines % (<10mm, & <25mm, 0.4" & 1"), and the greatest amount of SAG media % (+100mm, 3.9"). The electronic and high VOD blast produced more fines % than the baseline, and also the least amount of SAG media %.

Deck blasting trials were conducted with the aim to reduce top size (+400mm, 16") in the stemming zone of hard ore blasts. Gas bags were used to ensure a proper separation of the explosive column from the stemming zone. All other blast design parameters remained the same as baseline. The gas bag separation eliminated any desensitization of the explosive column by the intrusion of rock fragments from the stemming zone. Hence, a more effective and complete reaction of the explosive column should create more fractures in the rock, particularly in the stemming zone. Results showed a small reduction in the amount (%) of top size (5.9 % > +400mm, 16", compared with 6.4 % > +400mm, 16" in baseline) and warrants further testing of this method.

Now that the fragmentation results of the hard ore blasting trials have been discussed, the following section will outline the ore hardness and lithology characteristics of the blast trials.

Ore characterization – hardness and lithology

The best efforts were made by PKM engineers and geology to ensure the same lithology and ore hardness characteristics were maintained across all trials. All blasts were conducted in the hard ore (diorite and skarn) areas of the stage 5 central pit. Baseline measurements were predominately taken from the 430 RL and 420 RL, high PF trials were conducted on the 400 RL bench, and electronic detonator trials were conducted on the 380 RL bench. Figure 5 below shows an example of the lithology distributions encountered during the electronic detonator trials.

Belt cut samples from the trials underwent comminution test work. Results of the SMC test were used to determine the JK Drop-Weight index (DWi), and JK rock breakage parameters A and b. A*b values measure the resistance to impact breakage, with a high value of A*b indicating a 'soft' ore, whilst a low value indicates a 'hard' ore. The A*b results are shown in Figure 5. PKM samples are indicated by the vertical lines shown. This figure shows a similar range of rock strengths were tested across all trials.

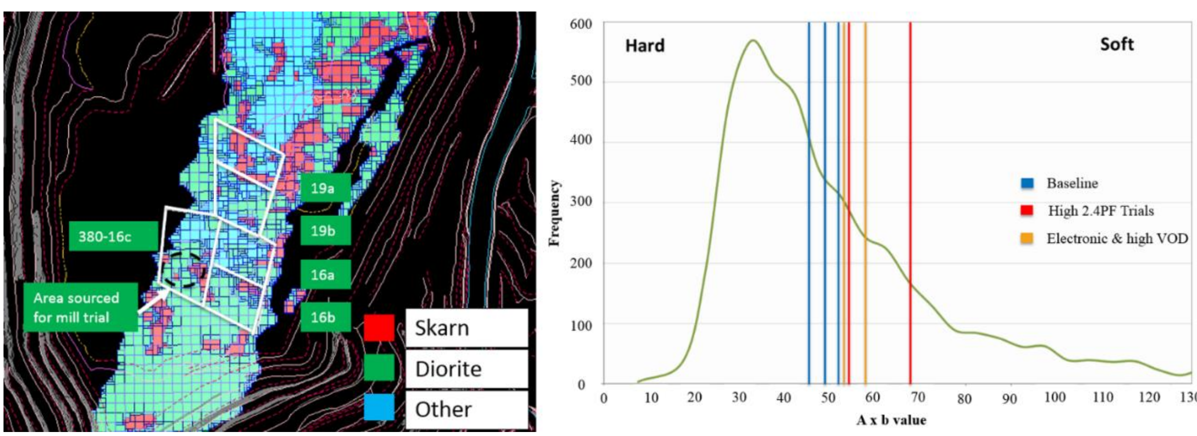


Figure 5. Ore lithology & Distribution of A x b values

Now that the ore hardness and lithology characteristics have been discussed, the following section will outline the trial success criteria and the 'value for money' approach.

Trial success criteria – 'value for money'

The aim of the trials was to identify the most effective way to improve mill throughput of harder ores. The success of each trial was based on a 'value for money' criteria. This criteria is a cost/benefit analysis that weighed-up the additional operating cost to implement the trial against the improvement in SAG mill tph.

Additional costs associated with the high 2.4 powder factor trials included greater drilling intensity, higher blast consumable costs, and a higher explosive usage. The high 2.4PF blasts cost 1.12 $/t, approximately 50% more than 1.6PF baseline (0.75$/t), and 43% more than the electronic and high VOD blast (0.78$/t). Additional costs associated with the electronic and high VOD blast included higher consumable costs of electronic detonators, and a higher unit cost of high VOD 90:10 emulsion:ANFO explosive. This cost, however, was partially offset by an increase in pattern size to maintain a PF of 1.6 kg/m3 (2.70 lbs/yd3).

Each trial was single-sourced through the mill for a period of 4 – 6 hours and the mill performance measured. The SAG mill throughput for each trial is shown below in Figure 6.

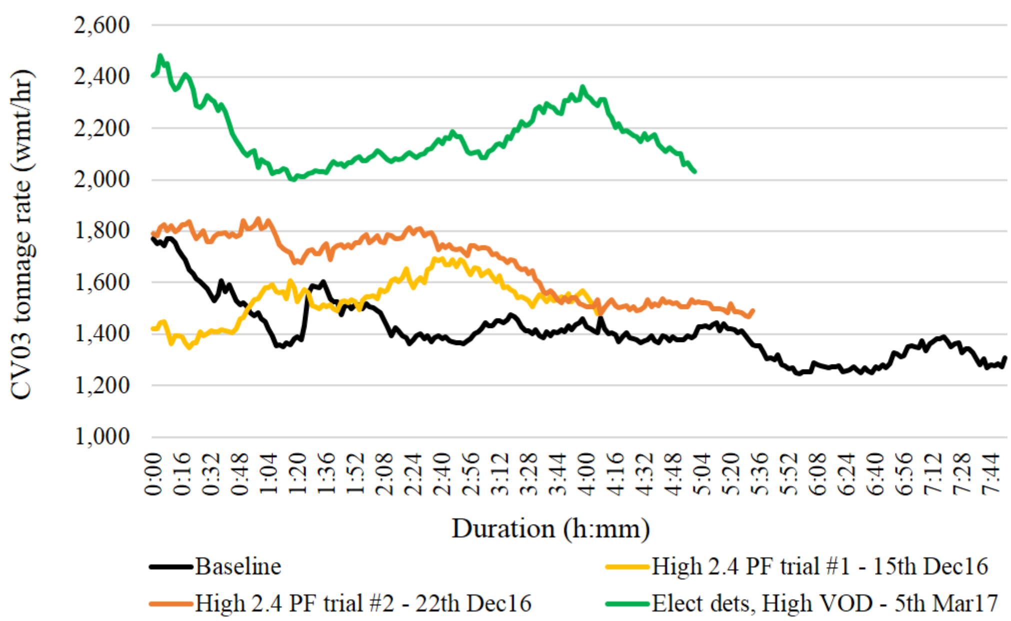


Figure 6. Blast trial SAG mill throughput

Mill throughput results in Table 4 show the high PF blasts achieved an average increase of 201 tph, whilst the electronic and high VOD blast achieved the greatest improvement of 757 tph, compared to baseline.

The 'value for money' success criteria is also given in Table 4 and is based on the PKM 2017 forecasted hard ore feed and mill operating hours. Using this measure, the lower the number - the better the value. Results show the electronic and high VOD blast produced the best 'value for money' measure (0.04 $/t), achieving an increase in mill throughput of 757 tph (increase of 54%), for an additional cost of only 0.03 $/t. The high 2.4 PF blast produced a poorer 'value for money' measure of 1.65 $/t, achieving an increase in mill throughput of 201 tph, for a much greater additional cost of 0.37 $/t.

Table 4. Mill throughput results and the 'value for money' success criteria

Blast Trial	**Baseline**	**High Energy 2.4PF**	**Electronic & high VOD**
Mill trial duration (hrs:mm)	8:00	9:45	5:15
Lith% diorite (idi), skarn (xkn)	69% (idi), 31%(xkn)	84% (idi), 10%(xkn)	85% (idi), 15%(xkn)
Blast PF (kg/m3)	1.6 (2.70 lbs/yd3)	2.4 (4.05 lbs/yd3)	1.6 (2.70 lbs/yd3)
Explosive type (Em. Blend)	70:30 Em:ANFO	70:30 Em:ANFO	90:10 Em:ANFO
Initiation: IH & IR (ms)	NONEL,25ms&42ms	NONEL,25ms&42ms	ED, 9ms & 30ms
SAG mill tph, mean	1,412	1,613	2,169
SAG mill tph, standard dev.	112	126	113
Increase in SAG mill tph %	-	14%	54%
Cost: additional operating ($/t)	-	0.37	0.03
Benefit: Increase in mill tph	-	201	757
Value for money ($/t)	-	1.65	0.04

Continuous Improvement

Measuring and tracking the implementation of blast design and blast performance outcomes, is important to ensure that blast designs are continuously improved. In early 2015, as part of PKM's blast improvement program, a blast data system was conceptualised. The system code was developed by consultants JKTech and has been written in the open-source software 'R'. The system has now been embedded in the PKM system since December 2016.

The blast data system operates by reading, compiling, and benchmarking the available data to give an overall view of blasting outcomes. An overall 'Blast Rating' (good, bad, acceptable) is then produced based on the measurements of blast QA/QC, digging performance, mill performance and fragmentation results. These key measurements are monitored through the blast data system and represented individually for each blast. Weekly and monthly blast performances are then monitored, as shown in Figure 7.

Blast Rating (Overall)						QA / QC						
Blast ID	Overall Rating	PF (kg/m3)	Lith1	Lith2	Type	QA/QC rating	Hole location (%)	Hole depth (%)	Stem height (%)	Product loaded (%)	Redrill (%)	Backfill (%)
S5-390-50	ACCEPTABLE	0.56	SLR	NA	Ore & Waste	Good	72%	80%	100%	74%	9%	11%
S5-380-15	ACCEPTABLE	1.36	VTF	IDI	Ore & Waste	Below Average	49%	55%	88%	49%	40%	2%
S5-380-19	ACCEPTABLE	1.59	VTF	IDI	Ore & Waste	ACCEPTABLE	66%	66%	95%	87%	24%	6%
S6-520-41	GOOD	0.70	SKN	DIO	Ore & Waste	ACCEPTABLE	65%	66%	94%	91%	15%	12%
S5-390-41B	BAD	0.80	RDB	N/A	Waste	ACCEPTABLE	57%	63%	98%	93%	23%	12%
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-

Production & Mill performance					Blast fragmentation						
Blast ID	Production rating	Average dig rate (s)	Average payload (t)	SAG throughput (tph)	Fragmentation rating	Overall rating (#)	Top size (mm)	P80 (mm)	>100mm (%)	50mm - 100mm (%)	<50 mm(%)
S5-390-50	ACCEPTABLE	137	83	2,521	ACCEPTABLE	8	369	117	23%	30%	46%
S5-380-15	ACCEPTABLE	100	87	2,070	ACCEPTABLE	7	741	184	32%	11%	57%
S5-380-19	ACCEPTABLE	110	87	2,423	BAD	10	843	236	42%	13%	45%
S6-520-41	GOOD	95	89	2,321	GOOD	6	673	112	22%	11%	67%
S5-390-41B	BAD	171	82	-	BAD	10	747	228	39%	13%	47%
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-

Figure 7. PKM drill and blast data system

Conclusion and Future Work

Increased SAG mill throughput at the PKM mine was achieved as a result of blast fragmentation optimization from improved blast initiation control with the use of electronic detonators, and with increased and more effective use of blast energy with higher VOD emulsion blend explosives. In addition, this success was achieved without any major cost implications, safety incidents or process plant set-backs.

Trials determined the electronic and high VOD 90:10 emulsion:ANFO blasts to have the best 'value for money', achieving an increase in mill throughput of 757 tph (an increase of 54% compared to baseline), for an additional cost to implement of only 0.03 $/t. This marginal increase in blasting costs will result in less work downstream at the primary crusher and ultimately the Concentrator communition circuit.

It was recommended to proceed with the full implementation of electronic detonators and high VOD emulsion blend explosives for all future PKM hard ore blasts. Continued monitoring of SAG mill performance will validate the trial results over the longer term.

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