Impact of Blast Fragmentation on Hydraulic Excavator Dig Time

I Brunton[1], D Thornton[2], R Hodson[3] and D Sprott[4]

ABSTRACT

Blast fragmentation size distribution and thus blast design have been found to have a direct impact on the load and haul cycle through excavator dig time and bucket payload. Previous studies have demonstrated that by reducing the excavator dig time and increasing bucket payload, significant improvements can be made in both productivity and unit cost. Simulation work reported in the literature indicates that a 20 per cent improvement in dig time may result in only a three per cent improvement in load and haul productivity and unit cost. At the same time, a ten per cent improvement in bucket payload will directly translate to a ten per cent improvement in load and haul productivity and unit cost. Based upon these findings, extensive laboratory and field work have been undertaken in the past to correlate blast fragmentation distribution to bucket payload. In contrast, the literature reports limited studies quantifying the impact of blast fragmentation on excavator dig time.

Field work was conducted at Placer Dome Asia Pacific's Granny Smith Mine (Wallaby Pit) in Western Australia, concentrating on quantifying the impact of blast fragmentation on the dig time of a Liebherr 994 hydraulic excavator (shovel attachment with 14 m^3 bucket). Fragmentation was assessed for each truck load of material using the *Split Desktop* system, while the excavator cycle analysis was conducted manually. Measured fragmentation P_{80} (fragment size at which 80 per cent of material passes) values ranged from 200 mm to 1200 mm.

The field study investigated the impact of various fragmentation parameters (P_{20}, P_{50}, P_{80}, cumulative per cent passing 250 mm size fraction, and uniformity index) on the average and total dig times. The results indicate that the fragmentation P_{80} provides the best correlation to average dig time (total dig time divided by the number of bucket passes to load a truck). The total dig time was found to be dependant upon the fragmentation P_{80} and the number of bucket passes to fill a truck. *Monte Carlo* simulation results, based upon these relationships, indicate a 26 per cent improvement in average dig time and a 12 per cent to 46 per cent improvement in total dig time (bucket passes ranging from 4 to 8), with a change in fragmentation P_{80} from 600 mm to 200 mm.

INTRODUCTION

In large open pit operations the truck and excavator fleet is typically one of the most costly components of the overall mining operation, contributing up to 60 per cent of the total mining cost (Allen *et al*, 1999). Significant mine cost savings can be made by small improvements in load and haul productivity. The literature indicates that the blast fragmentation distribution, and thus blast design, directly impact on excavator loading cycle time, non-productive cycle time (such as oversize removal, clean-up, and face raking), and bucket payload (Allen *et al*, 1999).

The Field work was conducted at Placer Dome Asia Pacific's Granny Smith Mine (Wallaby Pit) in Western Australia, as part of the Julius Kruttschnitt Mineral Research Centre (JKMRC) 'Blasting to Customer Specifications' (BTCS) Project, sponsored by Placer Dome Technical Services Limited, Vancouver, Canada. This study was limited to quantifying the impact of blast fragmentation on the dig time of a Liebherr 994 hydraulic excavator – other potential influences on dig time such as muckpile looseness, ability of the muck to rill, and operator digging strategy were not assessed. Fragmentation was quantified for each truck load of material using the *Split Desktop* system, while the excavator dig, swing, dump, and return times were recorded manually for each bucket pass.

BACKGROUND

Excavator dig time is defined as the period from when the bucket engages the muckpile to when it starts to swing or disengage. The major benefit of monitoring dig time over other 'diggability' measures is the ease in which the data can be collected. It has traditionally been used as an indirect measure of blasting performance (Kennedy, 1995). A number of factors impacting dig time have been reported in the literature including muckpile characteristics, excavator type, and operator proficiency and style.

A simulation study undertaken by Hawkes (1998) for a Hunter Valley coal mine, indicated that an improvement of 20 per cent in dig time resulted in a three per cent improvement in load and haul production and unit cost, when the haul fleet was optimised. For the same scenario, a ten per cent improvement in bucket payload directly translated to a ten per cent improvement in load and haul production and unit cost.

Due to the significant improvements brought about by increases in bucket payload by a modified blast fragmentation distribution, laboratory and field studies have been undertaken by a number of authors including Michaud and Blanchet (1996), Michaud *et al* (1997), Hawkes (1998), Allen *et al* (1999), and Singh *et al* (2001). The main conclusions reached have been that bucket payload is dependant upon the uniformity index (defines the slope of the cumulative fragmentation curve) and the characteristic size (fragment size at which 63 per cent of material passes) of the fragmentation distribution.

Limited studies quantifying the impact of blast fragmentation on excavator dig time are reported in the literature. These studies have generally related dig times to qualitative descriptions of muckpile characteristics such as fragmentation, looseness, heave, and 'diggability'. Several authors including McGill and Freadrich (1994), Grant *et al* (1995), Hawkes *et al* (1995), Hawkes (1998), and Doktan (2002) have reported a seven to 58 per cent improvement in average dig time for various improvements in muckpile characteristics. However, the literature to date has not quantified the direct impact of fragmentation distribution on excavator dig time.

Hawkes *et al* (1995) list a number of muckpile characteristics, which could impact excavator performance including fragmentation, looseness, and rilling properties. Additionally, a study conducted in a Canadian mine indicated an inverse correlation between the uniformity index of the fragmentation distribution and the average dig time (DOWNLINE, 1993).

Muckpile profile and fragmentation are also critical parameters when considering the type of excavator being used. Scott (1996) outlines the need for a shallow, spread out muckpile for a front-end loader to be productive, while a hydraulic excavator requires a steep face of intermediate height. Moodley *et al* (1996) identified that the dig time of different loader types were

---

1. Senior Research Officer, Julius Kruttschnitt Mineral Research Centre, University of Queensland, Isles Road, Indooroopilly Qld 4068. E-mail: i.brunton@uq.edu.au

2. Senior Research Officer, Julius Kruttschnitt Mineral Research Centre, University of Queensland, Isles Road, Indooroopilly Qld 4068. E-mail: d.thornton@mailbox.uq.edu.au

3. MAusIMM, Senior Mining Engineer, Placer (Granny Smith) Pty Ltd. E-mail: ray_hodson@placerdome.com

4. Senior Mining Engineer, Technology Group, Placer Dome Technical Services Ltd. E-mail: david_sprott@placerdome.com

influenced differently for a range of fragmentation distributions. The front-end loader for example is less influenced by fragmentation than a hydraulic excavator.

Operator proficiency and style have been demonstrated by a number of authors including Hendricks *et al* (1990), Daneshmend *et al* (1993), Hendricks *et al* (1993), and Hall and McRee (2001) to have a significant impact on dig time. Hall and McRee (2001) in their study of four operators found that the most variation in productivity occurred in the dig phase of the operating cycle and was due to operator digging tactics (ie bucket trajectory through the muckpile). Hendricks *et al* (1990) noted in their study that variations in operator digging tactics appeared to be motivated by changes in muckpile fragmentation.

WALLABY PIT FIELD STUDY

The Granny Smith Mine is located 950 kilometres northeast of Perth and 23 kilometres south of Laverton in Western Australia. The original Granny Smith deposit, which consisted of three discontinuous zones (Granny, Goanna and Windich), was mined out in 1995. Five satellite deposits (including Keringal, Jubilee and Sunrise) have also been depleted (Placer Dome, 2003a). Ore is currently supplied entirely from the Wallaby deposit, which is situated on the shore of Lake Carey, 11 km southwest of the existing Granny Smith mine.

The load and haul fleet consists of 13 Cat 785 trucks, two Cat 777 trucks, a Liebherr 994 hydraulic excavator (14 m^3 bucket), and a Liebherr 995 hydraulic excavator (23 m^3 bucket). Both excavators have shovel attachments, with the Liebherr 994 used predominantly for ore removal and the Liebherr 995 for waste removal. Excavation of ore material is undertaken in two flitches over a 10 m bench height, and is hauled 11 km to the run of mine (ROM) pad and primary crusher.

The field study concentrated on the fragmentation assessment and excavator performance of the Liebherr 994 (Figure 1) within the Stage 1 Cutback of the Wallaby Pit. Approximately seven excavator production hours were monitored during the study period. The excavator removed material from the top and bottom flitches of the 260 m to 250 m bench. During the trial, the Liebherr 994 was under-trucked with a combination of Cat 777 and 785 trucks, with a total of 77 trucks (29 Cat 777 and 48 Cat 785) being monitored. Other factors such as muckpile looseness and bucket trajectory were not considered in the study. To remove some variation from excavator performance, the same operator was used throughout the trial.

FIG 1 - The Liebherr 994 excavator monitored during the field study.

Geology

The Wallaby deposit occurs below Aeolian sand dunes and Tertiary lake clays and sands. A paleochannel runs along the western part of the deposit. An Archaean matrix-supported polymict conglomerate is at least 1200 m deep and is the dominant host rock of the pit. The mineralisation at Wallaby occurs along laterally flat shear zones that dip gently to the southeast (Placer Dome, 2003b).

Within the Stage 1 Cutback study area, five structural geology/geological domains have been identified (Brunton and Thornton, 2003). The location and description of these domains are summarised in Figure 2 and Table 1, respectively. The Liebherr 994 excavated material from the SD1, SD2, SD3, and Intrusive domains during the field trial.

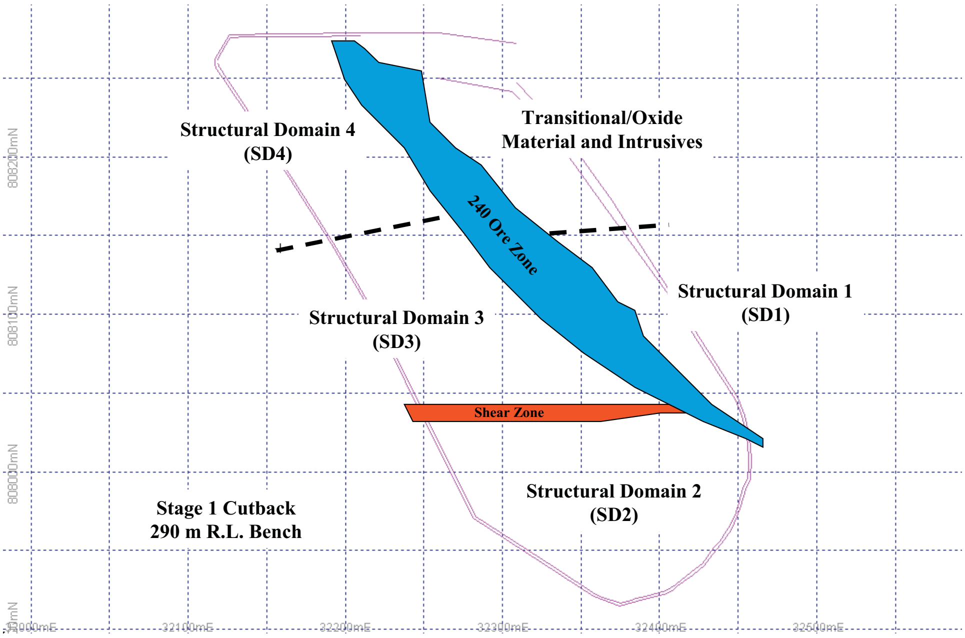


FIG 2 - Structural geology and geological domains in the field study area.

TABLE 1

Summary of structural geology and geological domains.

Structural domain	Location	Average UCS (MPa)	Geology	Description
SD1	Hangingwall of the 240 orebody, east wall.	216	Conglomerate with minor intrusives.	Blocky to massive rock mass producing coarse blast fragmentation.
SD2	South of the 240 orebody, south wall.			
SD3	Footwall of the 240 orebody, west wall.			Fractured rock mass producing fine blast fragmentation.
SD4		142		Fractured rock mass, some weathering, producing fine blast fragmentation.
Intrusive	Occurs in varying amounts throughout the pit, dominantly in the northern section of the cutback.	110	Intrusives consisting of monzonite and syenite dykes.	Massive rock mass producing coarse fragmentation.

Drill and blast design

The same drill and blast design parameters were used throughout the Stage 1 Cutback study area and are summarised in Table 2. Blast designs generally consisted of six rows (due to groundwater issues) and, where possible, were fired fully choked to reduce horizontal muckpile movement. Down-hole delays were 400 ms, while surface initiation was by reverse echelon or 'V' tie-ups with 25 ms inter-hole delays and 100 ms inter-row delays.

TABLE 2

Blast design parameters in field study area.

Bench height (m)	10.0
Hole ϕ (mm)	229
Spacing (m)	6.5
Burden (m)	5.5
Sub-drill (m)	1.8
Stemming height (m)	4.0
Explosive type	Powergel 2560
Powder factor (kg/m^3)	1.12

Due to the variable geology and structural geology across the study area and the excavation of a top and bottom flitch, variable fragmentation results were achieved, with measured P_{80} (fragment size at which 80 per cent of material passes) values ranging from 200 mm to 1200 mm. This wide range of P_{80} values provided an ideal situation to measure the impact of blast fragmentation on excavator dig time.

Blast fragmentation assessment

Fragmentation assessment was undertaken using the *Split Desktop* image processing program. The program computes the size distribution of rock fragments from grey scale images at various stages of the mining and milling process (Kemeny *et al*, 1999). Photographs were taken of truck tray backs when they were approximately three quarters full, with the width of the truck tray used to scale the image. The *Split Desktop* results were assumed to represent the fragmentation encountered by the Liebherr 994 during the complete truck loading cycle (since material from several buckets can be seen). This approach to fragmentation assessment is similar to that undertaken by Michaud and Blanchet (1996) in assessing the impact of fragmentation on truck fill factors. It should be noted that the analysis of individual buckets would provide more detailed data relating excavator performance to blast fragmentation. However, for this study it was not practical to manually analyse the number of fragmentation images that this would generate (in the order of 600 images).

Fragmentation image analysis systems cannot resolve particles smaller than a size determined by the pixel resolution and the scale of the image. To overcome this to some extent, *Split Desktop* uses a 'fines correction factor' where the size distribution of the 'unseen fines' is estimated from the image. The fines correction factor can be calibrated by physical sieving of the same material as photographed. While this is commonly done for conveyor belts, it is generally not practical to do it for the ROM due to the volume of material involved. For the fragmentation analysis undertaken, a fines correction factor of 50 per cent was selected. This means that 50 per cent of black pixels (used to represent particle edges and fines material) within the delineated *Split Desktop* image will count as fines material. This value was arbitrarily selected, based upon a medium fines correction outlined by Split Engineering (2001).

An example of a photograph taken of the truck back and used for fragmentation analysis is shown in Figure 3a. *Split Desktop* is used to automatically delineate the particles, with the results being manually edited. Figure 3b shows the output binary image generated by *Split Desktop*, with the delineated particles clearly visible. Grey areas indicate parts of the photograph that have been edited out of the sizing process and black areas denote parts of the photograph designated as fines. From the binary image, the blast fragmentation size distribution is calculated (Figure 3c).

Excavator performance

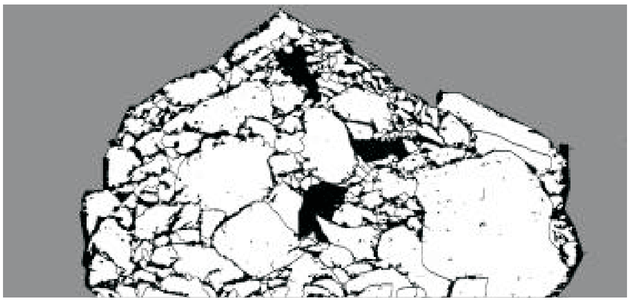
The basic excavator performance indicators of dig, swing, dump, and return times were monitored for the Liebherr 994 during the study. The dig time is the most sensitive component of the loading cycle to variation in muckpile characteristics. Dump time and the time for the operator to spot the next digging location (included in the return time for this study) could also be affected to a smaller extent. The influence of muckpile characteristics on swing and return time was considered to be negligible.

The first load of each truck usually has a period of non-productive time while the truck reverses under the raised bucket. This period starts when the excavator swings to the dump position and finishes when loading starts. Since this is determined by factors that have nothing to do with the muckpile, it has been removed from the analysis. Other delays such as waiting for a truck, excavator positioning, face clean up and minor breakdowns were excluded for the same reason.

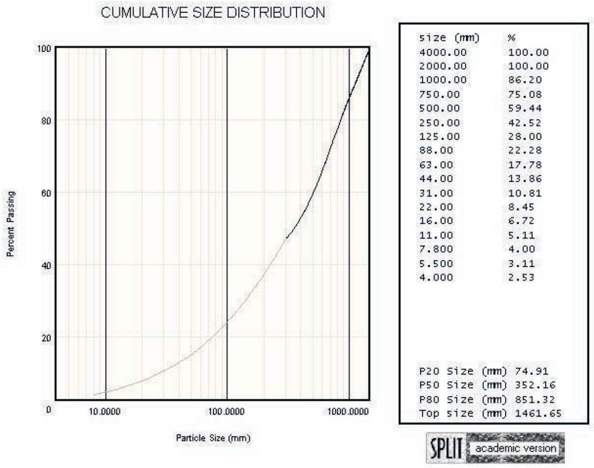
EXCAVATOR PERFORMANCE RESULTS

An analysis was undertaken of the individual excavator load cycle and complete truck load cycle times. The individual excavator load cycle time consists of the four basic cycle

(a) Truck tray back image



(b) *Split* output binary file



```
size (mm)       %
4000.00         100.00
2000.00         100.00
1000.00         86.20
750.00          75.08
500.00          59.44
250.00          42.52
125.00          28.00
88.00           22.28
63.00           17.78
44.00           13.86
31.00           10.81
22.00           8.45
16.00           6.72
11.00           5.11
7.800           4.00
5.500           3.11
4.000           2.53

P20 Size (mm) 74.91
P50 Size (mm) 352.16
P80 Size (mm) 851.32
Top size (mm) 1461.65
```

(c) *Split* fragmentation analysis output

FIG 3 - *Split Desktop* analysis process.

components (dig, swing, dump, return) for one excavator load. A complete truck load cycle time is the sum of the individual excavator load cycle times. As discussed previously, these times do not include delays such as truck spotting, waiting for trucks, excavator positioning, face clean up, and minor breakdowns.

Table 3 summarises and compares the resulting statistics for the individual excavator load cycle times. The total mean cycle time for the four components is 39.3 seconds. The greatest variations in the data (highest standard deviation) comes from the return and dig times. Variation in return time is high, due to the operator requirement to spot the next digging location (resulting in a longer return time). Variations in dig time can be attributed to a number of factors including muckpile characteristics and operator digging tactics.

TABLE 3

Summary of individual loading cycle times.

	Dig time (sec)	Swing time (sec)	Dump time (sec)	Return time (sec)*
Mean	17.1	6.6	4.9	10.0
Median	15.0	6.0	4.0	9.0
Standard deviation	7.3	2.2	2.7	4.7
Minimum	7.0	2.0	1.0	2.0
Maximum	56.0	18.0	29.0	46.0
Number of samples	578	578	578	501

* No return time after the last bucket for each truck.

The statistics of a complete truck loading cycle are summarised in Table 4. Additional information concerning the number of bucket passes to fill the truck and total dig time is also included. Due to the different payload capacities of the Cat 777 and 785 trucks, the results have been segregated into two components. It is clear that a Cat 777 will require, on average, less bucket passes to fill and, therefore, be faster to load, when compared to a Cat 785.

TABLE 4

Summary of the duration of each loading component for a complete truck load.

	Bucket passes		Total dig time (sec)		Truck load time (sec)	
	Cat 777	Cat 785	Cat 777	Cat 785	Cat 777	Cat 785
Mean	5.0	7.6	81.1	127.1	181.8	282.8
Median	5.0	8.0	77.0	127.0	175.0	274.0
Standard deviation	0.5	1.0	19.8	36.0	37.0	62.3
Minimum	4.0	6.0	47.0	67.0	113.0	189.0
Maximum	6.0	10.0	131.0	242.0	264.0	447.0
Number of samples	29	48	29	48	29	48

IMPACT OF BLAST FRAGMENTATION ON EXCAVATOR AVERAGE DIG TIME

An average dig time (total dig time divided by the number of bucket passes) was used to assess the impact of blast fragmentation on excavator performance. Due to variable geology across the bench and the excavation of a bottom and top flitch, a wide range of fragmentation distributions were measured for each truck, ranging from a P_{80} of approximately 200 mm to 1200 mm. A number of fragmentation distribution parameters were considered to impact average dig time including the P_{20} (fragment size at which 20 per cent of material passes), P_{50} (fragment size at which 50 per cent of material passes), P_{80}, top size, uniformity index, and cumulative per cent passing the 250 mm size fraction. To determine which of these parameters provided the 'best' correlation to average dig time a statistical analysis was undertaken. Figure 4 shows scatter plots of average dig time versus the various fragmentation distribution parameters, while Table 5 provides a statistical summary of the correlation between these parameters. For this analysis, the relationship between average dig time and the fragmentation parameters were assumed to be linear (solid lines in Figure 4).

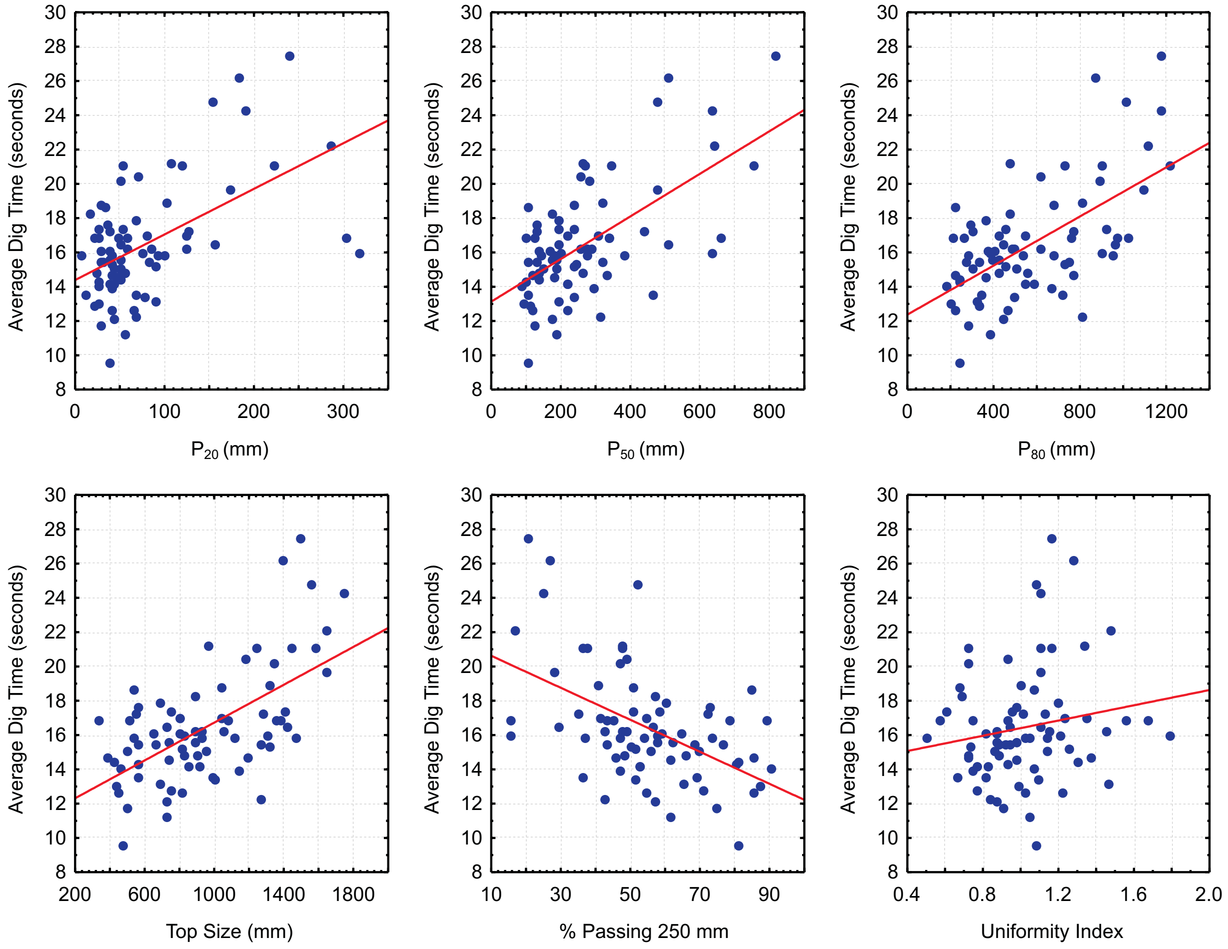


FIG 4 - Scatter plots of dig time versus fragmentation parameters.

TABLE 5

Statistical summary of correlation between average dig time and fragmentation parameters.

Fragmentation parameter	**Regression equation**	**No of samples**	**R^2**	***p***	**SEE**
P_{20}	Dig time = 14.39 + 0.03 P_{20}	77	0.29	$p < 0.001$	2.82
P_{50}	Dig time = 13.13 + 0.01 P_{50}	77	0.38	$p < 0.001$	2.64
P_{80}	Dig time = 12.37 + 0.01 P_{80}	77	0.40	$p < 0.001$	2.62
Top size	Dig time = 11.21 + 0.01 top size	77	0.36	$p < 0.001$	2.67
% passing 250 mm	Dig time = 21.56 – 0.09 % passing	77	0.28	$p < 0.001$	2.88
Uniformity index	Dig time = 14.18 + 2.22 uniformity index	77	0.03	$p > 0.1$	3.30

The results in Table 5 summarise the linear regression equation, R^2 (coefficient of determination), p (statistical significance), and standard error of the estimate (SEE) values for the relationship between average dig time and respective fragmentation parameters. R^2 values range from 0.0 to 1.0, and are an indicator of how well the model fits the data. An R^2 value close to 1.0 indicates that almost all of the variability with the variables specified in the model has been encounted for (Statistica, 2003). The highest R^2 value (0.40) was obtained for the average dig time – P_{80} linear regression line. The very low R^2 value (0.03) for the uniformity index indicates no relationship between the two parameters.

The p value is the probability of being wrong when accepting the hypothesis that there is a linear relationship. Low values of p (customarily $p < 0.05$) indicate a high likelihood that the observed correlations are real. Excluding the uniformity index, the p values for the other fragmentation parameters were below 0.05.

The standard error of the estimate (SEE) is a measure of the accuracy of predictions made with the regression line, and can be interpreted like the standard deviation both conceptually and computationally. The results indicate that the lowest standard error value (2.62) was obtained for the average dig time – P_{80} linear regression line.

Based upon the statistical results, P_{80} is considered to be the 'best' fragmentation distribution parameter to estimate average dig time (assuming a linear relationship). Figure 5 shows this relationship with the underlying dataset. It is apparent that as the fragmentation becomes coarser, the average dig time increases. For P_{80} values greater than about 800 mm, the gradient of the linear relationship might be expected to increase, resulting in a greater rate of change in dig time for any given P_{80} change. Further field data would be required to validate this assumption.

The wide scatter of data points in Figure 4 and Figure 5 are believed to be due to other muckpile and operator parameters affecting average dig time. These additional factors could include muckpile looseness and its ability to rill, and operator digging strategy (in particular bucket trajectory). Further study would be required to quantify the importance of these parameters on dig time.

EXCAVATOR TOTAL DIG TIME

Another important factor impacting on load and haul performance is the total dig time (summation of individual dig times to fill a truck). The total dig time is dependent upon a number of parameters, including, the payload of the truck, the number of bucket passes, and the individual dig times. The number of bucket passes to fill a truck is considered to be an indirect measure of the bucket payload. Figure 6 shows scatter plots relating total dig time, number of bucket passes, and fragmentation P_{80}, while Table 6 provides a statistical summary of the correlation between these parameters. The data in each plot is segregated into two components based upon the different load capacities of the Cat 777 and 785 trucks. For the analysis, the relationship between the various parameters was assumed to be linear (solid and dashed lines for Cat 777 and 785 trucks, respectively, in Figure 6).

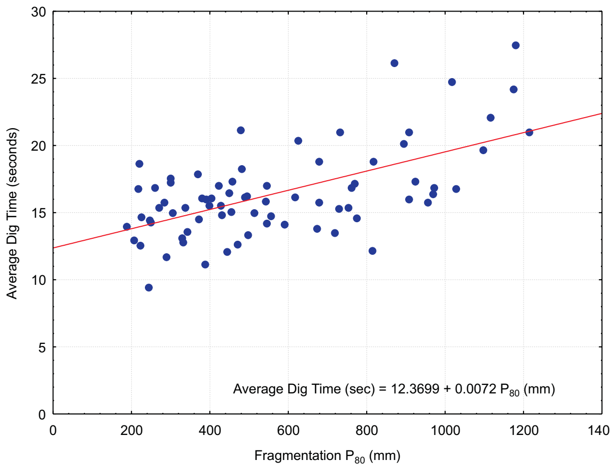


FIG 5 - Linear relationship between dig time and fragmentation P_{80}.

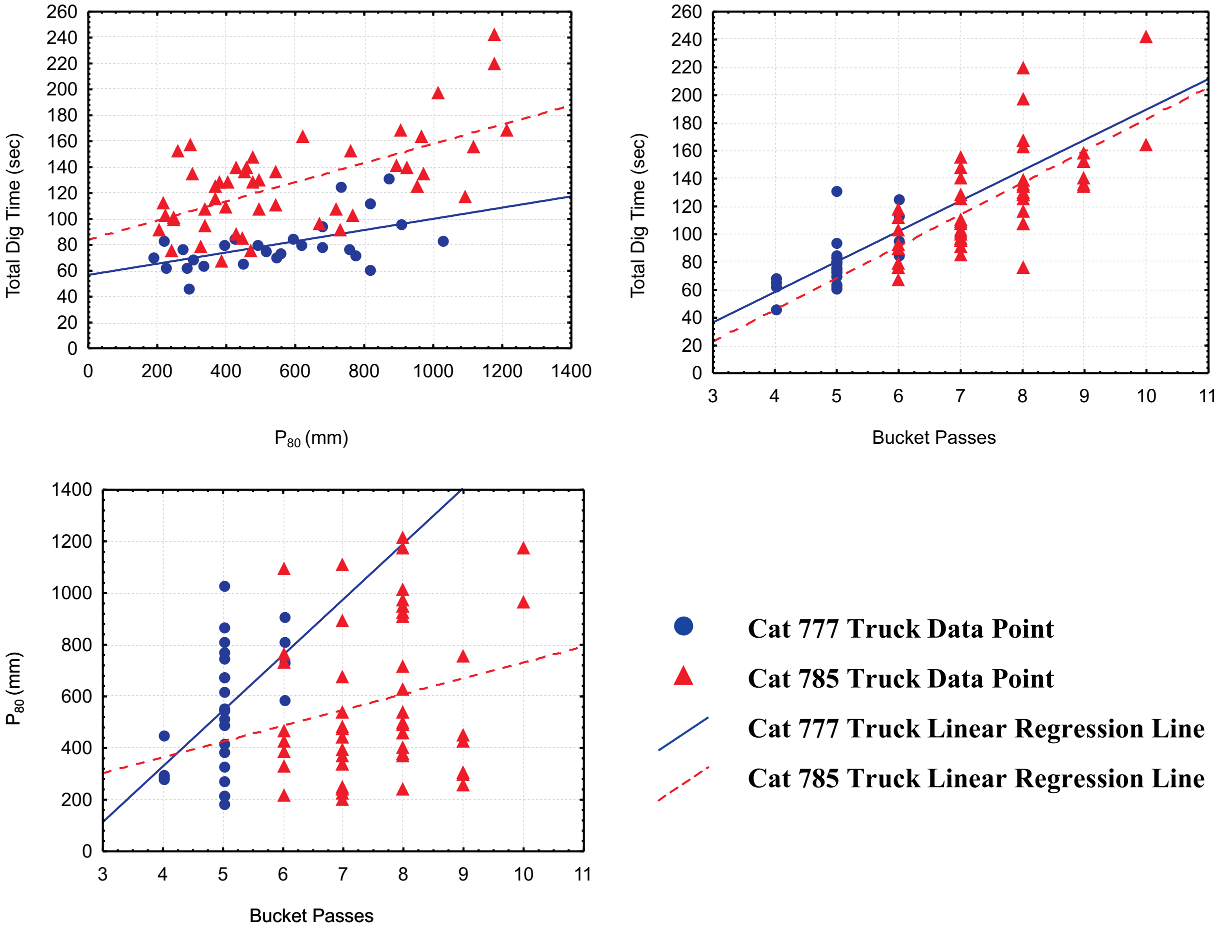


FIG 6 - Scatter plots of parameters impacting on total dig time.

The plots in Figure 6 and results in Table 6 indicate that the number of bucket passes and fragmentation P_{80} provide the clearest trends with respect to total dig time. A relationship between the P_{80} and the number of bucket passes is not evident. It can be concluded that blast fragmentation and the number of bucket passes to fill a truck have a direct impact on the total dig time. The number of bucket passes does not appear to be statistically related to blast fragmentation. It is believed that the number of passes is dependant upon other muckpile characteristics such as looseness and its ability to rill, as well as operator digging strategy.

Based upon the data collected, multiple variable regression analysis was undertaken for the Cat 777 and 785 trucks. The general purpose of this regression was to learn more about the relationship between several independent or predictor variables and a dependant or criterion variable. The dependant variable in the analysis was total dig time, while the independent variables were P_{80} and the number of bucket passes. The results of the multiple variable regression analysis are summarised in Table 7.

Figure 7 shows the observed versus predicted total dig time (using the equations in Table 7) for the Cat 777 and 785 trucks, respectively. The solid lines represent a perfect match between

TABLE 6

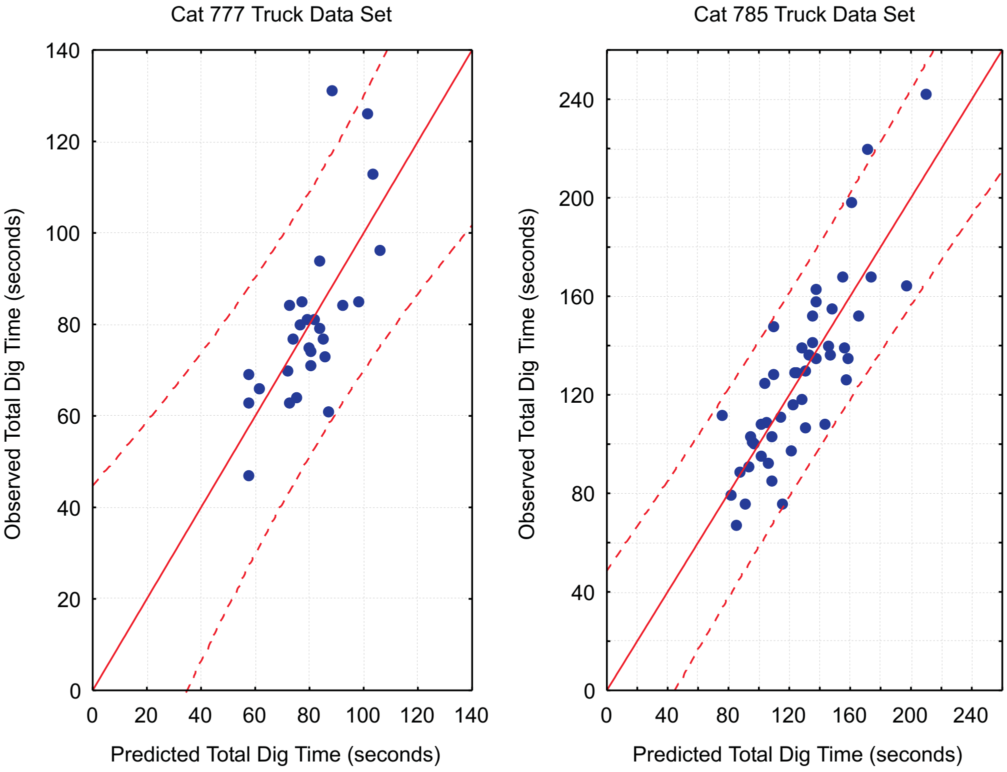
Statistical summary of correlation between total dig time, number of passes, and fragmentation P_{80}.

Truck	Regression equation	No of samples	R^2	*p*	SEE
Cat 777	Total dig time = 56.73 + 0.04 P_{80}	29	0.30	$p < 0.01$	16.05
Cat 785	Total dig time = 83.91 + 0.07 P_{80}	48	0.38	$p < 0.001$	28.45
Cat 777	Total dig time = -29.04 + 21.88 bucket passes	29	0.42	$p < 0.001$	14.73
Cat 785	Total dig time = -45.80 + 22.86 bucket passes	48	0.45	$p < 0.001$	27.07
Cat 777	P_{80} = -533.65 + 215.66 bucket passes	29	0.25	$p < 0.01$	212.20
Cat 785	P_{80} = 118.97 + 61.25 bucket passes	48	0.05	$p > 0.1$	298.20

TABLE 7

Summary of multiple variable regression analysis.

Truck	Multiple variable equation	No of samples	R^2	*p*	SEE
Cat 777	Total dig time = 16.66 bucket passes + 0.02 P_{80} – 16.16	29	0.49	$p < 0.001$	14.09
Cat 785	Total dig time = 19.23 bucket passes + 0.06 P_{80} – 52.25	48	0.69	$p < 0.001$	20.57


Cat 777 Truck Data Set

Cat 785 Truck Data Set

FIG 7 - Observed versus predicted total dig times.

the observed and predicted results, while the dashed lines are the 95 per cent prediction interval. The prediction interval gives information on individual predictions of the dependant variable. That is, a prediction interval for a predicted value of the dependant variable gives a range of values around which an additional observation of the dependant variable can be expected to be located (Statistica, 2003). The prediction interval is approximately ±30 seconds and ±40 seconds for the Cat 777 and 785 trucks respectively. In general, the predicted total dig times correspond relatively well to those observed in the field given the complex nature and variability of the problem. Further data is required to validate these relationships.

MODEL IMPACT OF BLAST FRAGMENTATION ON AVERAGE AND TOTAL DIG TIME

Based upon the linear and multiple variable regression results, an analysis was undertaken to investigate the impact of fragmentation P_{80} and number of bucket passes on model average and total dig times. Figure 5 shows the model linear relationship between average dig time and fragmentation P_{80}. Figure 8 shows the resulting percentage improvement in average dig time for a decrease in P_{80} based upon this model linear relationship. For a given initial and final P_{80} value, the percentage improvement in model average dig time can be determined. For example, a reduction of P_{80} from 1200 mm (initial) to 700 mm (final) would result in an approximate 20 per cent improvement in model average dig time.

Figure 9 shows the model total dig time, based upon the multiple variable equations in Table 7, for various fragmentation P_{80} and number of excavator bucket passes. The two graphs shown are for Cat 777 and 785 trucks, respectively.

Impact of variability on model results

Due to the variability of observed results with respect to each regression equation, *Monte Carlo* simulation techniques were used to calculate the 90 per cent confidence interval (5th and 95th percentiles) and mean for each model result. From the previous regression analysis, the variability of observed results from the regression line was observed to be normally distributed.

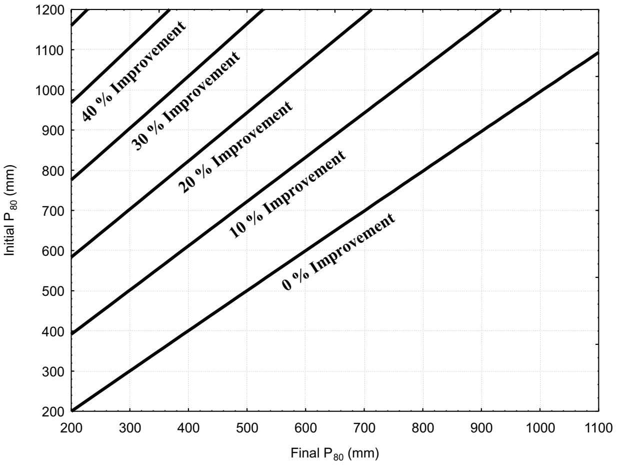


FIG 8 - Per cent improvement in model average dig time from initial to final P_{80}.

Table 8 summarises the average and total dig time regression equations, with ‘n’ denoting the normal distribution for each *Monte Carlo* simulation. The standard deviation of the normal distribution is equal to the SEE in Table 5 and Table 7 for the average and total dig times respectively. The mean for each normal distribution is set to zero for the purposes of the analysis.

A number of scenarios were modelled investigating the impact of changes in fragmentation P_{80} on average and total dig times. For each scenario, thirty thousand *Monte Carlo* simulations were conducted to calculate the per cent improvement in dig time for various changes in fragmentation. Table 9 and Table 10 summarise the modelling results for the average and total dig times respectively.

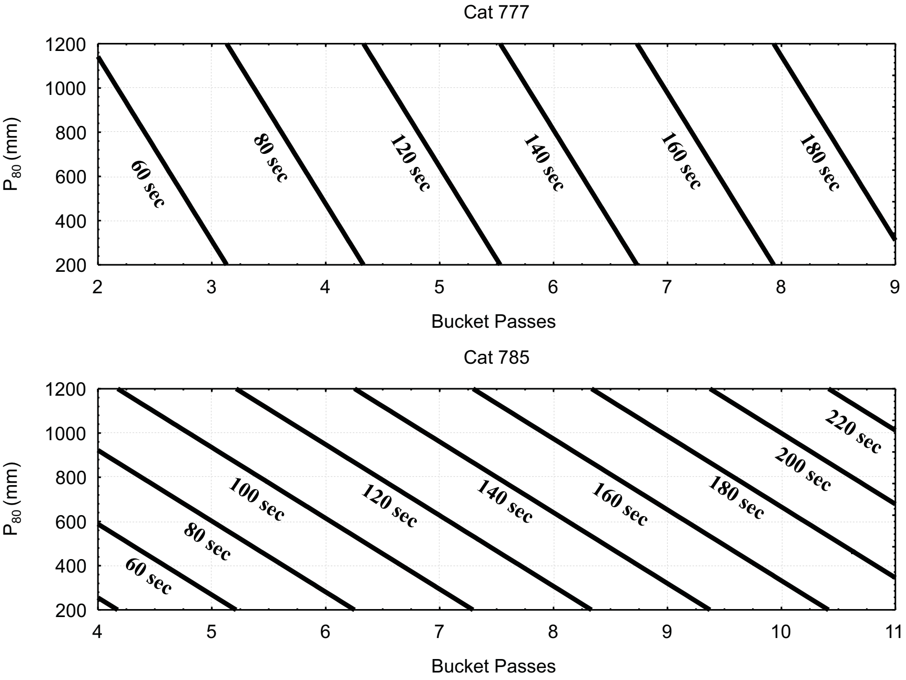


FIG 9 - Model total dig time for Cat 777 and 785 trucks for various P_{80} and bucket passes.

TABLE 8

Regression equations for Monte Carlo simulations.

Truck	Regression equation	Normal distribution (n)	
		Mean	Standard deviation
All	Average dig time = 12.37 + 0.01 P_{80} + n	0.00	2.62
Cat 777	Total dig time = 16.66 bucket passes + 0.02 P_{80} – 16.16 + n	0.00	14.09
Cat 785	Total dig time = 19.23 bucket passes + 0.06 P_{80} – 52.25 + n	0.00	20.57

TABLE 9

Impact of fragmentation P_{80} on model average dig time.

Initial P_{80} (mm)	Final P_{80} (mm)	Per cent change in model average dig time		
		5th Percentile	Mean	95th Percentile
1200	200	6	59	132
1000	200	-2	48	117
800	200	-11	37	103
600	200	-20	26	88
400	200	-29	15	74

The results in Table 9 indicate that for an extreme change in fragmentation P_{80} from 1200 mm to 200 mm, the mean percentage improvement in model average dig time is 59 per cent. For a more realistic P_{80} reduction from 600 mm to 200 mm, the mean percentage improvement in model average dig time is 26 per cent. These results correlate well to those published in the literature.

For model total dig time, a fragmentation P_{80} reduction from 1200 mm to 200 mm results in a mean percentage improvement from 26 per cent to 49 per cent for the Cat 777 trucks and 59 per cent to 96 per cent for the 785 trucks, depending upon the number of passes assumed. For a P_{80} reduction from 600 mm to 200 mm, the mean percentage improvement in model total dig time varies from 12 per cent to 25 per cent for the Cat 777 trucks and 26 per cent to 46 per cent for the 785 trucks, depending upon the number of passes assumed.

The 90 per cent confidence interval is wide, with negative changes in average and total dig times being reported in some instances with a decrease in fragmentation P_{80}. This indicates that a reduction in fragmentation produces an increase in dig time for some cases. Due to the relatively wide scatter of observed dig times with respect to P_{80} during the field trial, a wide 90 per cent confidence interval would be expected. Further data collection and investigation of other key muckpile and operator characteristics may reduce this confidence window.

CONCLUSIONS

It has been demonstrated in this field study that a relationship exists between the Liebherr 994 excavator average dig time and blast fragmentation. The analysis of field data investigated the impact of fragmentation distribution P_{20}, P_{50}, P_{80}, per cent material passing 250 mm, and uniformity index on average dig time. The results indicate that the fragmentation P_{80} provides the best correlation to average dig time. A linear regression model was developed to relate the Liebherr 994 average dig time to fragmentation P_{80}.

The total dig time for the Liebherr 994 was found to be dependant upon the fragmentation P_{80} and number of bucket passes. No correlation was found to exist between the number of bucket passes and fragmentation P_{80}. It is believed that the number of passes is dependant upon other muckpile characteristics, such as, looseness and its ability to rill as well as operator digging strategy. A multiple variable model was developed based upon field data to relate excavator total dig time to the P_{80} and number of bucket passes. Predicted total dig times correspond relatively well to those observed in the field, given the complex nature and variability of the problem.

TABLE 10

Impact of number of bucket passes and fragmentation P_{80} on model total dig time.

Case	Truck	Bucket passes	Initial P_{80} (mm)	Final P_{80} (mm)	Per cent change in model total dig time		
					5th Percentile	Mean	95th Percentile
Case 1	Cat 777	4	1200	200	-18	49	152
		5	1200	200	-14	34	102
		6	1200	200	-13	26	75
	Cat 785	6	1200	200	12	96	238
		7	1200	200	10	72	165
		8	1200	200	9	59	127
Case 2	Cat 777	4	600	200	-35	25	115
		5	600	200	-29	16	78
		6	600	200	-24	12	59
	Cat 785	6	600	200	-25	46	157
		7	600	200	-21	32	107
		8	600	200	-18	26	83

Monte Carlo simulation results using the linear and multiple variable regression equations indicate a 26 per cent improvement in average dig time and a 12 per cent to 46 per cent improvement in total dig time (bucket passes ranging from 4 to 8) with a change in fragmentation P_{80} from 600 mm to 200 mm. These results correlate well to those published in the literature to date. The 90 per cent confidence interval is wide, with negative changes in average and total dig times being reported in some instances with a decrease in fragmentation P_{80}. This indicates that a reduction in fragmentation produces an increase in dig time for some cases. Further data collection and investigation of other key muckpile and operator characteristics may reduce the 90 per cent confidence window.

Further work is planned to conduct a cost-benefit analysis on the impact of improved fragmentation on load and haul costs. The load and haul costs constitute approximately 60 per cent of the entire mining cost at the Wallaby Pit (Hall, 2003). Therefore, any improvement in these costs could have a significant impact on the overall mining cost. A previous simulation study reported in the literature indicates a three per cent improvement in load and haul productivity and unit cost for a 20 per cent improvement in dig time.

It should be noted that this study only investigated the impact of blast fragmentation on excavator average and total dig time. The study indicates that a degree of variability is associated with the relationship between blast fragmentation parameters and dig time, with an overall trend of increased dig time with coarser fragmentation. It is believed that some of the variability within the data could be contributed to other factors such as muckpile looseness, ability of the muck to rill, and operator digging strategy. Further study is required to confirm the impact of these variables on excavator performance. Additionally, further study is required to quantify the impact of blast fragmentation on bucket and truck fill factors, and excavator and truck maintenance costs.

ACKNOWLEDGEMENTS

The authors would like to thank Placer Dome Asia Pacific for granting permission to publish this paper. Additionally, Placer Dome Technical Services Limited and Placer (Granny Smith) are thanked for their support of the Blasting to Customer Specifications (BTCS) Project.

REFERENCES

Allen, F, Hawkes, P and Noy, M, 1999. Bucket Fill Factors – A Laboratory and Field Study with Implications for Blasting, in *Proceedings EXPLO '99*, pp 43-46 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Brunton, I and Thornton, D, 2003. Phase 2 – BTCS Project at Granny Smith (Placer Dome), JKMRC Internal Confidential Report, pp 52 (JKMRC: Brisbane).

Daneshmend, L, Hendricks, C, Wu, S and Scoble, M, 1993. Design of a Mining Shovel Simulator, in *Proceedings International Congress on Mine Design*, pp 102-110 (Ontario).

Doktan, M, 2002. A Preliminary Study of the Impact of Blast Fragmentation on Load and Haul Productivity at Porgera, JKMRC Internal Confidential Report, pp 84 (JKMRC: Brisbane).

DOWNLINE, 1993. Optimising Productivity, *DOWNLINE, A Periodical for Explosive Users*, Issue 22 August (ICI Explosives: Canada).

Grant, J R, Little, T N and Bettess, D, 1995. Blast Driven Mine Optimisation, in *Proceedings EXPLO '95*, pp 3 - 10 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Hall, A and McRee, R, 2001. Characterisation of Operator Practice on Large Hydraulic Excavators, in proceedings *'No Mine is an Island' Tenth Annual JKMRC Conference*, pp 107-125 (JKMRC: Brisbane).

Hall, J, 2003. Personal communication, June.

Hawkes, P J, Spathis, A T and Sengstock, G W, 1995. Monitoring Equipment Productivity Improvements in Coal Mines, in *Proceedings EXPLO '95*, pp 127-132 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Hawkes, P, 1998. Using Simulation to Assess the Impact of Improvements in Drill and Blast on Down Stream Processes, in *Proceedings Mine to Mill 1998*, pp 209-217 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Hendricks, C, Peck, J and Scoble, M, 1990. Integrated Drill and Shovel Performance Monitoring for Improved Fragmentation and Productivity, in *Proceedings Third International Symposium Rock Fragmentation by Blasting*, pp 9-20 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Hendricks, C, Daneshmend, L, Wu, S and Scoble, M, 1993. Design of a Simulator for Productivity Analysis of Electric Mining Shovels, in *Proceedings Second International Symposium Mine Mechanisation Automation* (Lulea).

Kemeny, J, Girdner, K, Bobo, T and Norton, B, 1999. Improvements for Fragmentation Measures by Digital Imaging: Accurate Estimation of Fines, in *Proceedings Sixth International Symposium for Rock Fragmentation by Blasting – Fragblast 6*, pp 103-109 (South African Institute of Mining and Metallurgy: Johannesburg).

Kennedy, O, 1995. Dig Indexes will put Blast Engineers on Path to Profit, *Australia's Mining Monthly*, March, p 24.

McGill, D M and Freadrich, J, 1994. The Effect of Fragmentation on Loader Productivity, in *Proceedings 12th Annual Conference on Explosives and Blasting*, pp 128-135 (International Society of Explosive Engineers: Austin).

Michaud, P R and Blanchet, J Y, 1996. Establishing a Qualitative Relation between Post Blast Fragmentation and Mine Productivity: A Case Study, in *Proceedings Fifth International Symposium on Rock Fragmentation by Blasting – Fragblast 5* (Ed: B Mohanty), pp 389-396 (Balkema: Rotterdam).

Michaud, P R, Lizotte, Y C and Scoble M J, 1997. Rock Fragmentation and Mining Productivity: Characterisation and Case Studies, in *Proceedings 23rd Annual Conference on Explosives and Blasting Technique*, pp 275-279 (International Society of Explosive Engineers: Austin).

Moodley, L, Cunningham, C and Lourens, M, 1996. Measuring the Effect of Blasting Fragmentation on Hard Rock Quarrying Operations, in *Proceedings Fifth International Symposium on Rock Fragmentation by Blasting – Fragblast 5* (Ed: B Mohanty), pp 353-359 (Balkema: Rotterdam).

Placer Dome, 2003a. http://www.placerdome.com/operations/grannysmith/granny.html, June.

Placer Dome, 2003b. http://www.placerdome.com/operations/grannysmith/granny_geol.html, June.

Scott, S, 1996. *Open Pit Blast Design Analysis and Optimisation*, pp 16-17 (Julius Kruttschnitt Mineral Research Centre: Brisbane).

Singh, S, Glogger, M and Willock, D, 2001. Effect of Fragmentation on Loader Efficiency, in *Proceedings 27th Annual Conference on Explosives and Blasting Technique*, pp 77-87 (International Society of Explosives Engineers).

Split Engineering, 2001. Using Split-Desktop Software Step 4: Compute Size, in computer software Split Desktop Version 2.0 Help File.

Statistica, 2003. http://www.statsoft.com/textbook/stathome.html, June.