Full scale SLC draw trials at Ridgeway Gold Mine

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Abstract

More than 30 full scale draw trials have been carried out at Ridgeway Gold Mine between 2001 and the present. These draw trials, intended to improve business performance through an increased understanding of granular flow, have yielded significant new information on behaviour of the SLC system at Ridgeway. This understanding has enabled the mine to better forecast grade recovery, develop improved ring designs, and significantly cut the cost of mining.

1 INTRODUCTION

Ridgeway Gold Mine (Ridgeway), a part of Newcrest Mining Limited's Cadia Valley Operations, is located approximately 20km south of Orange, some 250km west of Sydney, Australia (Figure 1). The Ridgeway deposit is a copper/gold porphyry, located at depths of between 600m and 1,300m. Current reserves at the mine are 38Mt at 2.32g/tAu and 0.72%Cu. It is mined using sublevel caving (SLC), producing at 15,000 tpd. A targeted success factor is maximizing ore recovery and minimizing dilution. Feasibility predictions for life of mine resource conversion were 102% tonnes for 94% metal at a grade factor of 92%.

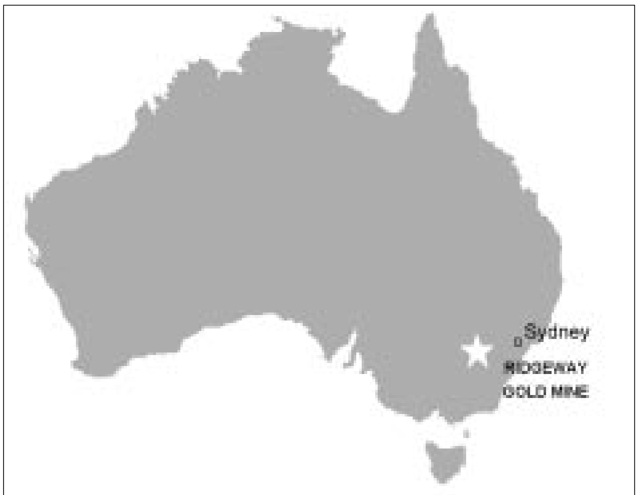

Figure 1: Location of Cadia Valley Operations

Figure 2 shows the shape of a typical blast ring used at the mine. In order to promote interaction between draw envelopes, pillar widths are designed to be as small as possible without creating geotechnical difficulties (8m).

Ring burdens of 2.6m are used and are dumped forward by 10° to improve drawpoint and ring stability. The mine layout was established from the principles of interactive draw (Janelid 1974; Bull and Page, 2000). The aim is to achieve interaction of the individual draw envelopes to allow material at the sides of the ring to move more freely, reduce hang-ups and increase width of the draw envelope. Drawpoints on individual levels are retreated in a flat front. Small tonnage cycles (typically approximately 15% per cycle) are extracted from individual drawpoints before

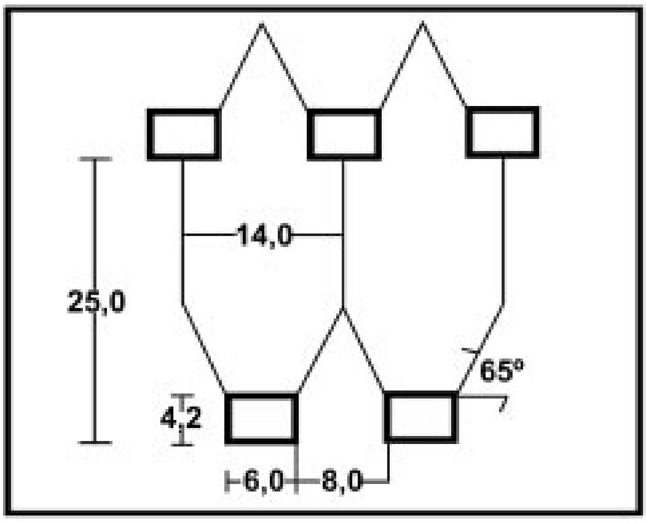

Figure 2: Section looking north showing ring geometry used at Ridgeway

moving to adjacent drawpoints. The cycle is repeated until the designated extraction is reached.

To assess the recovery effectiveness at Ridgeway, a series of full scale field experiments commenced in 2001. The aims of these experiments were:

- Development of an understanding of the granular flow mechanisms controlling dilution entry;
- Assessment of the effectiveness of interactive draw procedures;
- Quantification of recovery and dilution in order to allow better grade forecasting; and
- Development of improved ring design parameters.

This paper reports the current findings from these experiments.

2 TRIAL PROCEDURES

The design of the Ridgeway marker trials is based on similar experiments carried out at Grängesberg and Kiruna Mines in Sweden. (Janelid, 1972; Gustafsson, 1998)

Marker drill fans are drilled within the burden of an unfired ring, and loaded with uniquely coded markers made of steel pipe. The markers are 250mm long to approximate the mean particle size of blasted rock (previously established by a fragmentation measurement program). Markers, filled with cement to increase durability, are installed using the mine's production charging vehicle and grouted into place to ensure that they do not move when nearby rings are fired.

Figure 3: Marker being installed from production charging vehicle.

For the majority of the experiments each 2.6m burden contained three evenly spaced marker fans of 6 or 7 holes. The marker fan planes were spaced 650mm apart to allow estimates of depth of the draw and back-break to be made. Figure 4 shows a typical marker fan. Markers were placed at one metre intervals along each hole in the fan allowing for redundancy. A total of approximately 300 markers were present in each of the marker rings fired.

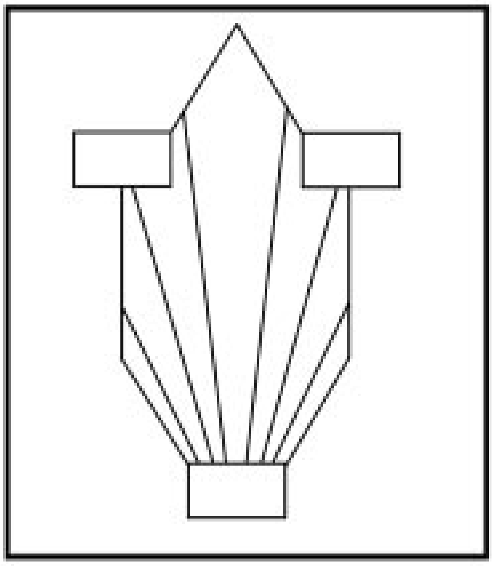

Figure 4: Section looking north showing typical marker fan

After each ring was fired, the broken ore (with the markers) was loaded from the drawpoint and tipped into the orepass. The markers traveled down the orepass to the crusher feed level, through the crusher onto the underground conveyor system, where they were extracted using the tramp steel electro-magnets. Tests indicated that 100% of markers tipped into the orepass and ore handling system were recovered.

Analysis of marker collection timing relative to ring extraction was used to assess incremental ring recovery and dilution. A full description of the experimental method is covered elsewhere (Power 2003a).

For each of draw trials, a number of different parameters were collected. These included:

- Total recovery (% volume);
- Recovery of each marker plane (% area);
- Maximum width of draw;
- Maximum depth of draw; and
- Back-break (% volume).

Ring recoveries were interpreted by wire framing the recovered marker plane sections and calculating the resultant three-dimensional volumes.

3 TRIAL RESULTS

3.1 Primary recovery and dilution entry

The first trial, using a single marker ring, indicated that material was flowing to the drawpoint through a narrower and shallower zone than had been expected. After 120% draw, the draw envelope was 11.9m at its widest point, and approximately 1.8m at its deepest (shallower than the 2.6m fired burden).

This first experiment indicated 'dilution' was arriving at the drawpoint after less than 20% draw of the design ring tonnage. Interpretations indicated that volume of the draw envelope was too small to have delivered the tonnages drawn from the drawpoint without dilution being present. The origin of the dilution was identified as from the depleted drawpoint above. This interpretation was also supported by the evidence of recovered shotcrete encased mesh and bell wire used in the level above.

While early dilution entry had been recorded previously elsewhere (Gustafsson, 1998; Hustrulid, 2000), it was hypothesized that this 'diluting' material originated from in front of the fired ring rather than above it.

The initial trial results stimulated interest in further experiments. Additional marker rings were installed and a number of drill and blast parameters were varied in these trials, with the aims of reducing drill and blast costs and increasing recovery. Whilst these trials successfully validated reducing drill and blast costs by 20%, they provided limited leverage on improving recovery and dilution. Primary recovery (the percentage of the fired ring recovered from the level on which it was fired) continued at 60%. While this was lower than originally expected (based on empirical dilution entry curves), the effect of ore recovery on lower levels had not yet been quantified.

Figure 5 shows typical primary recovery results from a draw marker trial. For this trial (as for the majority), two marker rings were monitored side by side, and drawn interactively as part of a panel of four adjacent rings. Adjacent rings are staggered and this section represents a plane 0.65m forward of the blast ring on the left (in XC0), and 1.3m forward of the blast ring on the right (in XC2).

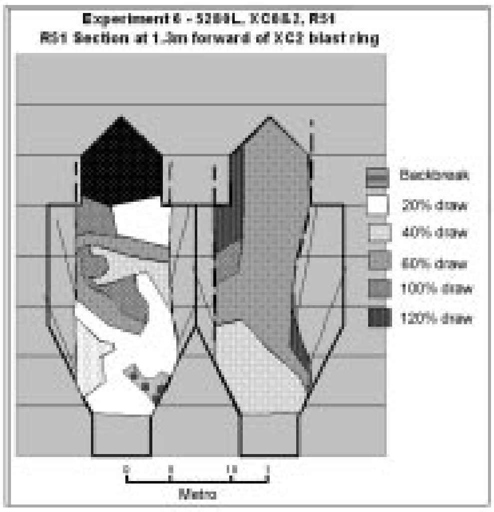

Figure 5: Typical results from a marker trial (section looking north)

The experimental findings show the widths of the draw envelopes to be narrower than the width of the fired rings. To date, no evidence of interaction between two adjacent draw envelopes has been found. Comparisons from isolated experiments also indicate interactive draw procedures do not significantly widen draw envelopes at Ridgeway.

The episodic nature of flow is also apparent from the experimental measurements. Rather than showing the even flow profiles it can be seen that flow proceeds in stages from different parts of the ring.

Dilution entry from above is shown where material from the top of the ring is being recovered in XC0, at low draw quantities. At less than 1m forward of the blast ring, ore is flowing from an area in contact with a depleted drawpoint above.

Ore from a depth of 1.3m in XC2 also reaches the drawpoint at a much later stage than the ore closer to the solid face in XC0. Figure 6 shows a section through the centre of XC0 (two consecutive rings were monitored in this trial).

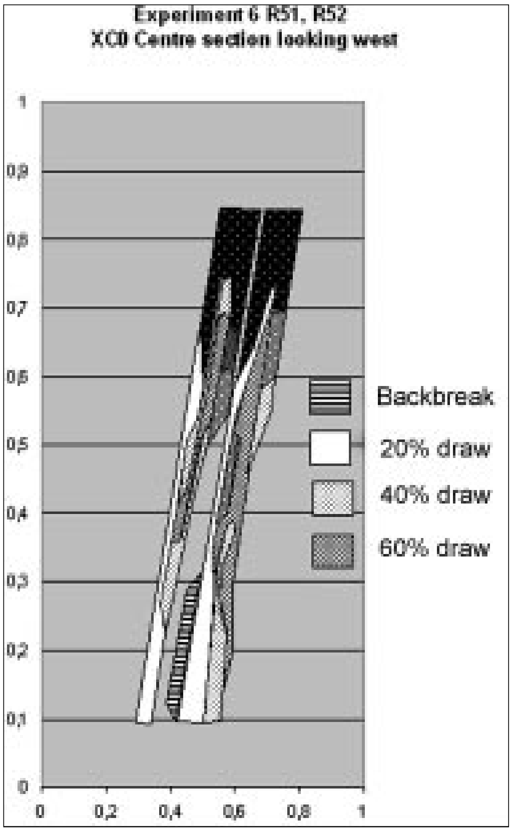

Figure 6: Typical trial section looking west

This is typical of most of the experiments, where the draw envelope consistently developed up the solid face of the ring, and then subsequently deepened. The late arrival of the ore at the top of the ring suggests this material may be coarser than most of the ring, and may have been pre-empted by the flow of dilution from one of the cross cuts above.

3.2 Secondary recovery

While primary recovery results are of value, it is unrealistic to expect that all material is recovered on the level from which it is fired. Ore which is recovered on the level immediately below is classified at Ridgeway as secondary recovery. Because each marker was uniquely coded, all recovered markers were associated with the ring from which they were fired, even though production from that ring may have long since ceased. Figure 7 shows that in addition to the material recovered as primary recovery, a significant portion of the fired ring is also regularly recovered as secondary recovery.

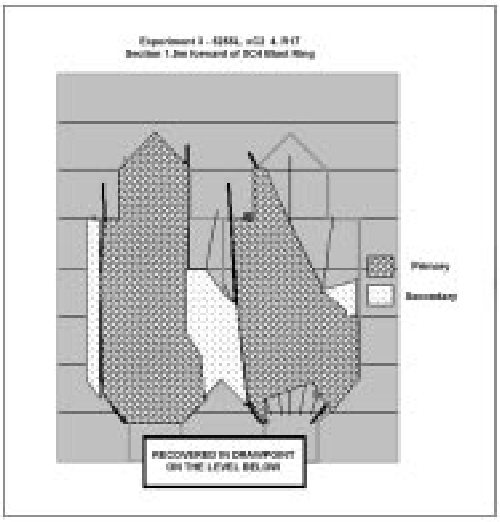

Figure 7: Typical secondary recovery results

As the primary draw envelopes reach the top of the fired ring at less than 20% draw, they have the opportunity to draw up into previously unrecovered material from the sides of the rings above, increasing total recovery for these rings. While the behaviour of primary recovery draw envelopes can be predicted to some degree, secondary recovery behaviour is more variable.

3.3 Tertiary recovery

Material recovered from two or more levels below that from which it was fired is classified as tertiary recovery at Ridgeway. Production below the Ridgeway marker trials has not progressed to the extent that conclusive tertiary recovery results can be recorded. However reconciliation and modeling work discussed in Section 4 indicate that a value of approximately 85% at 100% draw is currently being achieved. This does not take into account the additional recovery that will be gained if a low cost overdraw option is taken at the end of the mine life.

3.4 Experimental findings summary

While individual experiments show the draw process to be a rather chaotic, analysis of the collected results shows a system that can be characterized relatively accurately. Both primary and secondary recovery show a 95% confidence interval of little more than 5% This is to some degree a function of the favourable sample size.

Table 1 summarises the primary and secondary results of the Ridgeway marker trials to date.

Table 1: Summary of results

	Primary recovery (%)	Primary + Secondary recovery (%)
Average	59.1	75.0
Standard deviation	10.2	10.0
95% confidence interval	5.4	5.6
Upper limit	53.7	69.4
Lower limit	64.5	80.6

When Tertiary recovery is accounted for, this indicates that as applied at Ridgeway, the SLC mining method can yield recoveries and grade factors approaching those achieved at open stoping mines, at significantly higher production rates, and lower costs.

3.5 Discussion

While knowledge of ring recovery is important, it is an understanding of the underlying flow and blasting mechanisms that enables business improvements.

From one perspective, the relatively narrow draw envelopes seen in the Ridgeway experiments were expected. Results of full scale experiments carried out previously in Sweden (Janelid 1972; Gustafsson, 1998) and discussions with personnel from Kiruna Mine (Sellden, 2001) indicated that the draw envelope might be expected to diverge from the edge of the drawpoint at approximately 70°. While interactive draw has been considered as a means of widening the draw envelope, evidence from these trials indicates that this may be valid for physical modeling experiments only (Janelid, 1974).

The finding that the draw envelope was shallower than the fired burden was an unexpected outcome of these experiments. Before the experiments, it was believed that dilution entry was from in front of the fired ring, and full depth (the ring burden) of draw was achieved. This dilution entry 'from the front of the ring' hypothesis had also been postulated by others (Gustafsson, 1998).

3.6 Visual Observations

It has been considered a possibility that the marker experiments themselves had affected the behaviour of the rings being fired, and subsequently the flow of the broken ore. While changing the system is likely to have some affect on the blast performance, the magnitude of such an effect is unknown, and draw markers are the best means of quantifying draw performance currently available.

Observations made visually in rings without markers indicate that the shallow draw phenomenon is also apparent when marker trials are not present.

These observations were made possible through changes in Ridgeway's geological model which rendered a crosscut developed at the edge of the orebody sub-economic. This cross cut was therefore used as an observation drive, from which the behaviour of rings fired on the level below could be observed. Figure 8 shows the location from which these observations were made.

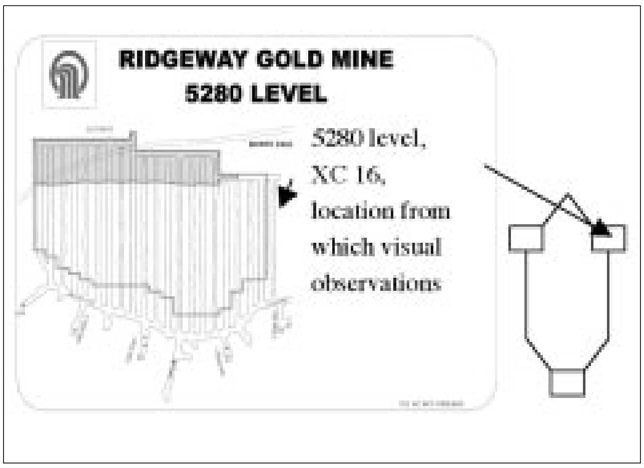

Figure 8: Observation drive at Ridgeway

From this drive, mechanisms controlling the shallow draw envelope could be observed independently in rings which were not monitored using markers. Photographs taken from this drive can be seen in Figures 9 and 10.

The scale at the bottom of the photograph in Figure 9 is 900mm long, indicating that the width of the opening is approximately 1.5m. This is similar to the depth of many of the draw envelopes measured in the marker trials. Note that the rock mass on the right side of the photo appears to be relatively solid. In some cases similar seemingly solid walls collapsed as draw from the level below progressed. Figure 10 shows a photograph of another ring taken from the same drive. Note in this figure the arch of rock, a remnant of the initial rock mass structure.

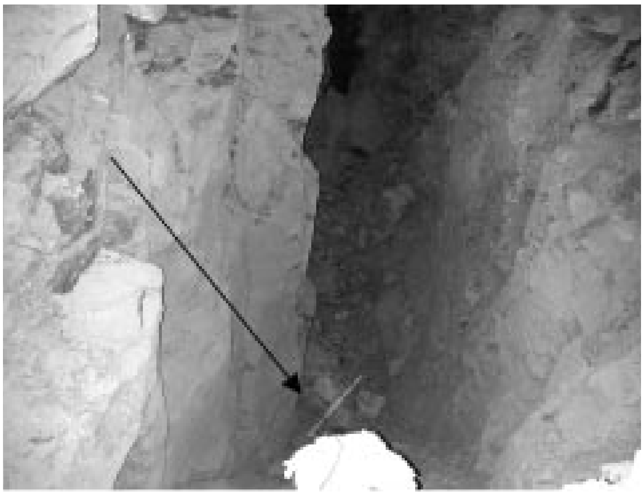

Figure 9: Photograph taken from observation drive.

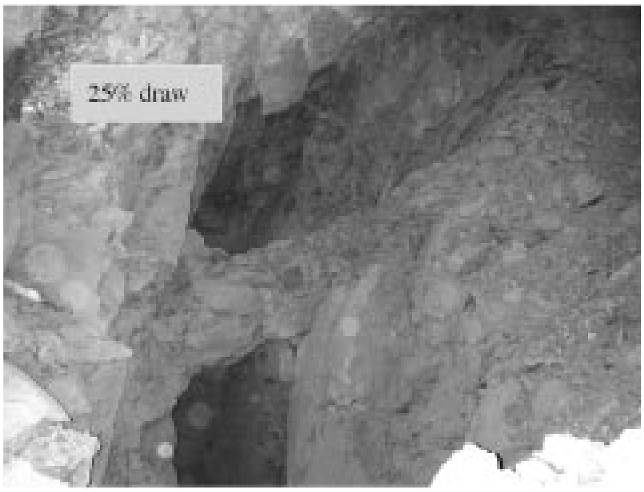

Figure 10: Photograph taken from observation drive

Many similar observations led to the development of a hypothesis similar in some ways to that of Hustrulid (2000), suggesting that the space available for the broken rock in a fired SLC ring was inadequate to allow swell to occur effectively.

While the rockmass closer to the blast appeared to be more heavily affected, and flowed preferentially, the rockmass further away from the blast was less heavily affected. Often individual rock fragments in this region were not disassociated from their neighbouring fragments. Therefore when draw from the level below began creating space, only the material closest to the blast was sufficiently broken to move, while the material forward of the blast plane was conditioned but could not be always be mobilized.

Obviously under such circumstances, dilution entry from the waste side of the ring would be impossible and draw would naturally progress vertically. Note that the photograph in Figure 10 was taken at 25% draw, indicating that early dilution entry from above was likely to have occurred. It is also interesting to point out that in most cases, the LHD operator on the level below had little indication that this effect was taking place in the fired ring above. Occasionally a drawpoint opened up completely, but until before the draw marker program, this was seen purely as the effect of a hang-up, rather than the result of a regular pattern of fired ring behaviour.

These results indicated that a drill and blast issue may have been a driving factor behind the shallow draw behaviour. A subsequent intense focus on this aspect of the operation did indicate some drill and blast issues which were addressed. This produced a general reduction in hang-up frequency from 25% to 15%, and a reduction of approximately 20% in drill and blast costs. To date however, no significant changes in draw behaviour or recovery have been seen in marker experiments.

4 FLOW MODELLING

Advances have also been made in the field of flow modelling. Until quite recently, validated flow modelling could not be carried out for caving mines (Rustan, 2000). However with the recent development of detailed validation information (Power, 2003a), and advances in numerical modeling techniques (Pierce, 2003, Sharrock et. al. 2004, Romer 2004) realistic numerical simulations will soon be achievable.

To augment these, a relatively simple preliminary technique for the construction of recovery curves under the SLC system has been developed (Power, 2003b). This technique for construction of recovery curves was developed through the application of Wilhemy's Law to the problem of ring depletion. Wilhemy's law states that the velocity of a chemical reaction is proportional to the concentration of the reacting substance, where:

- a = the initial concentration of the reagent;
- x = the amount transformed; and
- t = time.

This law is described by the relationship:

$$dx / dt = k (a-x), \quad 0 \le x \le a. \qquad (1)$$

This situation can be seen as analogous to draw from a SLC ring in that the amount of material from a certain recovery class, which can be drawn from a fired ring (e.g. Primary recovery) is proportional to how much of the ring remains to be drawn. Curves were developed for the four recovery classes: primary, secondary, tertiary and external (material from outside the mining limits).

The following parameters were substituted for those listed above:

- a = the percentage of the ring initially available for recovery;
- x = the amount of ore recovered at any stage of draw;
- t = the stage of draw at which this occurs.

The boundary conditions listed in Table 2 were then used in conjunction with this equation to create the recovery class specific equations shown in equations 2, 3 and 4. The boundary conditions used for tertiary recovery were based on analysis of copper and gold recoveries on the upper levels of the mine with respect to concentration of these metals in the sub-economic mineralized halo above the orebody. (Power 2003b). A dilution entry point of 20% was used for all curves as material entering as dilution is generally a mixture of material from many different sources (i.e. secondary, tertiary and external).

Table 2: Ridgeway boundary conditions

Recovery Class	Known recovery (%)	Known stage of draw (%)	Dilution entry point (%)
Primary	60	120	20
Secondary	75	120	20
Tertiary	85.3	100	20

Primary recovery:
$x = t, 0 \le 20,$
$x = 20 + 100 (1-e^{-kt}),$
where $k = 1/80 \log_e (80/40), t > 20$ (2)

Secondary recovery:
$x = t, 0\le 20,$
$x = 20 + 120(1-e^{-kt}),$
where $k =1/100 \log_e (120/65), t > 20$ (3)

Tertiary recovery:
$x = t, 0 \le 20,$
$x = 20 + 325.2 (1-e^{-kt})$, where
$k =1/80 \log_e (325.2/258.9), t >20$ (4)

Figure 11 shows a plot of the resulting recovery curves.

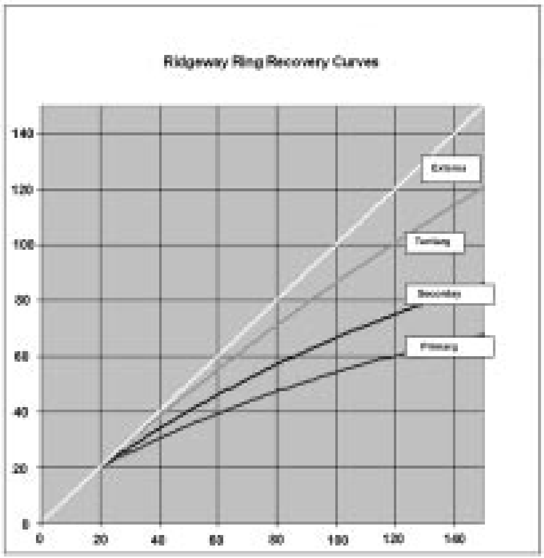

Figure 11: Ridgeway ring recovery curves

For the practical purposes, these equations can be simplified according to the following:

Primary recovery:
$x = t, 0 \le t <20;$
$x = 20 + 0.5(t-20), 21 \le t <50;$
$x = 35 + 0.4(t-50), 51 \le t <80;$
$x = 47 + 0.35(t-80), 81 \le t <110;$
$x = 57.5 + 0.3(t-110), 111 \le t <140.$ (5)

Secondary recovery:
$x = t, 0 \le t <20;$
$x = 20 + 0.65(t-20), 21 \le t <50;$
$x = 39.5 + 0.55(t-50), 51 \le t <80;$
$x = 56 + 0.5(t-80), 81 \le t <110;$
$x = 70.95 + 0.45(t-110), 111 \le t <140.$ (6)

Tertiary recovery:

$x = t,\ 0 \le t < 20;$
$x = 20 + 0.9(t-20),\ 21 \le t < 50;$
$x = 47 + 0.8(t-50),\ 51 \le t < 80;$
$x = 71 + 0.75(t-80),\ 81 \le t < 110;$
$x = 93.2 + 0.7(t-110),\ 111 \le t < 140. \quad (7)$

Note that equations 2 - 7 are valid only for the current set of Ridgeway boundary conditions (Table 2). If a new set of boundary conditions is used it is necessary to reassess the equations using the general law as a starting point.

Table 3 shows evaluations of mine performance using different methods: feasibility data, values predicted using the new recovery curves, and reconciled values. This indicates that the new recovery curves are relatively accurate. Over the life of the mine, it is estimated that the grade factor will be approximately 7% lower than predicted at feasibility.

Table 3: Comparison of feasibility, predicted and reconciled metal recoveries

	Tonnes Drawn (%)	Metal Recovered (%)	Grade Factor (%)
	Performance to date		
Feasibility	82	81	99
Predicted	82	73	88
Reconciled	82	71	87
	Predicted life of mine		
Feasibility	102	94	92
Predicted	102	86	85

Given any set of boundary conditions, this method allows realistic recovery curves to be generated for the analysis of modified SLC designs before mining begins. Additional confidence is gained from knowledge that the curves are based on a proven scientific relationship and have been validated against full scale experiments in a real mining environment.

5 CONCLUSIONS

The ongoing draw marker program in place at Ridgeway has allowed significant steps to be made in understanding the fundamental relationship between blasting and flow in SLC mining and has contributed to a significant reduction in drill and blast costs. Newcrest considers the ongoing operational use of draw marker tests is an important business tool to enable successful application of SLC.

Current efforts at Ridgeway center on creating a modified SLC geometry which produces the optimal combination of three important inter-dependant factors: drill and blast design, granular flow behaviour and geotechnical response of the rock mass.

It is expected that the results of marker trials at Ridgeway and other mines in the near future will result in further significant improvements in the understanding of granular flow in SLC mines.

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