Tracking Hardness and Size:
Measuring and Monitoring ROM Ore Properties
at Highland Valley Copper

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presented at:

Mine to Mill - 98

October 11 to 14, 1998

Brisbane, Australia

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ABSTRACT

Highland Valley Copper recently implemented a system of measuring run-of-mine (ROM) ore properties and monitoring their effect on both mine and mill performance. These properties are principally ore hardness and size.

For some years, Highland Valley Copper has been estimating ore hardness using knowledge of the geological conditions combined with previous mill experience. These estimates assist with ore blending and forecasting. The new system outlined in this paper, is the next step in this program. Using the latest technology available in mining equipment, ore properties are tracked through the in-pit crushing, conveying and stockpile network to the mill feed using the mine dispatch system and some simple models.

The result is a continuous update on the ore hardness going to all five grinding lines along with predictions for the future. This will give both operators and process control systems alike the opportunity to shift targets and/or change operating conditions to suit the ore properties.

Ore size distributions - from the muckpile to the mill - are measured using video cameras and the WipFrag image analysis software. These measurements can provide feedback on the control of blast fragmentation as well as optimise mill throughput. For example, the effects of segregation can be minimised through the manipulation of stockpile feeders.

Highland Valley Copper is in an almost unique situation of knowing the amenability of the ore they are treating through systems put in place to measure and monitor the ore properties in real-time. This information can then be used by the mine and mill engineers to improve the productivity and efficiency of their operations.

BACKGROUND

In most mining operations, the run-of-mine (ROM) ore marks the interface between the mine and the concentrator; the completion of mining and the start of milling. Like a manufacturing plant, the mill processes the raw material supplied by the mine. Quality control monitoring of the raw material is essential for manufacturing to remain competitive, yet this is not common practice in the mining industry.

Highland Valley Copper (HVC) has been logging and monitoring ore hardness in both its Valley and Lornex open pits for many years. Contour maps showing hardness values for every bench in the pits are drawn up and used for mine planning and forecasting. Yet hardness is only one of the sources of ore variability; the other is size or fragmentation.

In 1996, the drill hole diameter used for HVC production blasts was increased in order to reduce mining costs. The effect on the mill due to the coarser fragmentation was a slow but steady decline in throughput. Learning from this experience, Highland Valley is now far more aware of the influence of fragmentation on mill performance.

In order to quantify and understand the effect of feed size and hardness on mill throughput, a system for measuring and monitoring ROM ore properties was developed. The system uses existing computer networks and the latest in mining technology to track ore hardness and size from the blast to the mill.

ORE HARDNESS

Ore hardness can be defined for mining applications as how difficult a material is to fracture, crush and grind to a size suitable for treatment. Laboratory tests typically subject a small sample of rock to a standard set of conditions and measure either the energy required to reduce the sample to a known size or the size resulting from a known input energy.

Examples include the Triaxial or Brazilian test for compressive or tensile strength, the Julius Kruttschnitt Mineral Research Centre (JKMRC) Pendulum and Drop Weight tests for ore breakage characteristics and the Bond Grindability Test for Bond Work Index (JKMRC, 1996 pp 50 - 81).

Geological-Based Hardness Estimates

Since 1977, Highland Valley Copper has operated a blending program using hardness estimates based on mineral, geological and local ground conditions. A paper published in the *SAG '96 Proceedings* by Mitchell and Holowachuk (1996) details the method involved and the effects on blending at HVC.

The method of assigning ore hardness is based on the presence and the degree of thermal alteration of the rock. In the Valley and Lornex pits, there are four major types of thermal alteration: potassic, propylitic, phyllic and argillic. Argillic alteration has been divided into five categories, from weak to intense, with the rock being softer with the degree of alteration. A fifth type of alteration, silicification or re-entrant by silica-bearing fluids, is associated with quartz porphyry dykes. These porphyry dykes are only weakly affected by the other forms of alteration.

Table 1 below lists a number of defined rock types, with the degree of argillic alteration and presence of silicification. The degree and type of alteration is noted by the presence of indicator minerals such as clays, chlorite and sericite. A geologist who is trained in the method, will identify the alteration from the indicator minerals and categorise the rock hardness into one of the types. Local ground conditions (eg. faults) and muckpile fragmentation are included in the overall determination of the rock hardness value.

Table 1: Defined Alteration/Rock Types at Highland Valley Copper

(Mitchell and Holowachuk, 1996)

Degree of Argillic Alteration	Silicification or Re-entrant?	Rock Type	"Hardness" [#] (A line equivalent)
weak	yes	quartz porphyry	300 - 550 tph
moderate	yes	quartz porphyry	550 - 950 tph
weak	no	diorite/granodiorite	600 - 750 tph
weak - moderate	no	diorite/granodiorite	750 - 950 tph
moderate	no	diorite/granodiorite	950 - 1200 tph
intense	yes	quartz porphyry	950 - 1400 tph
moderate - intense	no	diorite/granodiorite	1200 - 1500 tph
intense	no	diorite/granodiorite	1500 - 2400 tph

[#] "A line equivalent" refers to the estimated throughput of HVC's A grinding line treating this ore.

In order to make the hardness numbers relevant to the Highland Valley operation, they have been calibrated to one of the five grinding lines (labelled A through E) based on operating experience over many years. The hardness values are quoted in terms of "A line equivalent" or the throughput of a 10 metre diameter semi-autogenous (SAG) mill with a standard ball charge. Table 1 shows the range of hardness values (in tph) for each of the rock categories. A considerable variation in throughput is shown for each category due to local ground conditions and the degree of fragmentation.

While this method has proven itself to be quite useful and accurate in predicting mill throughput, it relies heavily on the experienced eye of the geologist. A more objective and automated method of inferring rock hardness was needed to base the new system of tracking ore properties from the mine to the mill.

Drill-Based Hardness Measurements

Since 1996, the mine has begun fitting their equipment with global positioning systems (GPS). For some years, Highland Valley has used the Modular Mining Dispatch system for shovel and truck scheduling and the step up to GPS-based navigation was a natural progression (Richards, 1997). Currently, one of the shovels and all of the production drills are fitted with GPS.

The navigation system installed on the drills uses software developed by Aquila Mining Systems of Canada. The package installed at HVC included a material recognition system that determines a rock "Work Index" based on the drill parameters. As the drill progresses down the hole, a Work Index value is recorded every metre based on the rate-of-penetration. Figure 1 shows the operator screen during the drilling of a hole. The numbers on the right of the screen and the colour-coded column indicate the Work Index values for every metre of hole.

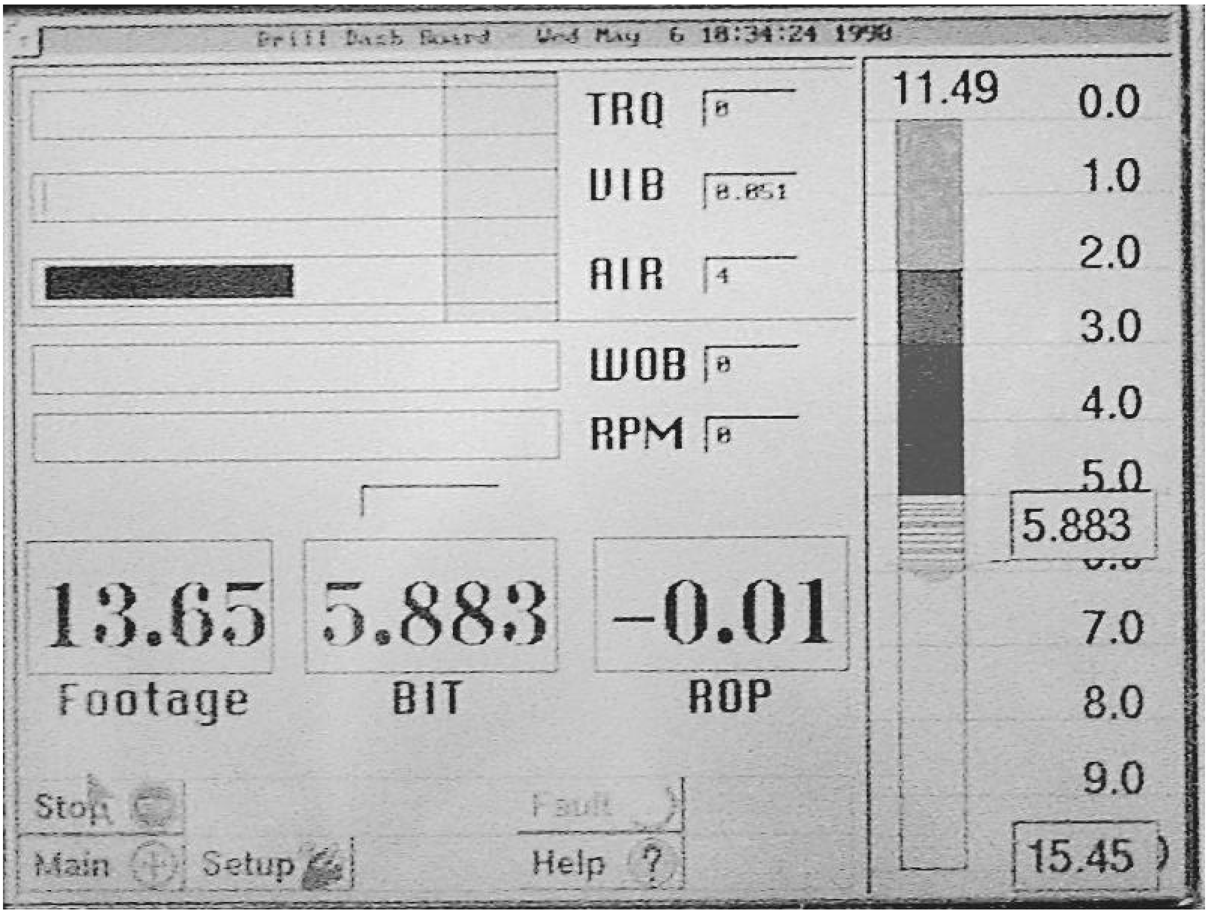

Figure 1: Aquila System Drill Operator Screen

According to Aquila (Anon., 1998), rock hardness can be inferred from measurements of the rate of penetration, the torque in the drill stem and the vibrations in the mast head. (The hole diameter, rotary speed and pulldown pressure are assumed to be constant.) The torque is related to the power required to break the rock through shearing while the vibrations reflect the energy required for compressive failure of the rock. Tool life or bit wear is ignored as after the initial period to seat the inserts, the bit remains fairly constant until the final 10% of life when the cones jam under bearing failure. The vibrations in the drill stem are measured in the mast head or lateral beam and, although dampened by the elasticity of the drill rod, reflect the shape of the vibrations at the drill bit.

The Aquila system requires field testing to calibrate the values to site conditions. More accurate calibration can be achieved through the use of borehole cameras for geophysical logging of individual drillholes. After calibration, the Work Index values (between 0 and 100) should represent the full range of rock hardness that will be encountered.

At this stage, the Work Index numbers are averaged for each drill hole (excluding the first two metres) and logged to file. These data are entered in the mine planning software where contour maps showing the range of hardness across the bench are generated. Figure 2 below shows an example of such a contour map where each drill hole is approximately 8 to 10 m apart. (Note the variation in Work Index values across the bench with the rock getting harder from right to left.)

ROM TRACKING

The Aquila values provide an objective, automated measure of rock hardness on a hole-by-hole basis (approximately 10 m spacing or every 80 m^2). Should it be required, rock hardness could be logged in more detail by recording the downhole measurements rather than an average for the hole. With GPS shovel navigation capable of centimetre resolution, it would be possible to assign a rock hardness value to each bucket load (a thought for the future).

Currently, the mine planning software assigns an average Aquila hardness number to each ‘polygon’ in the pit.

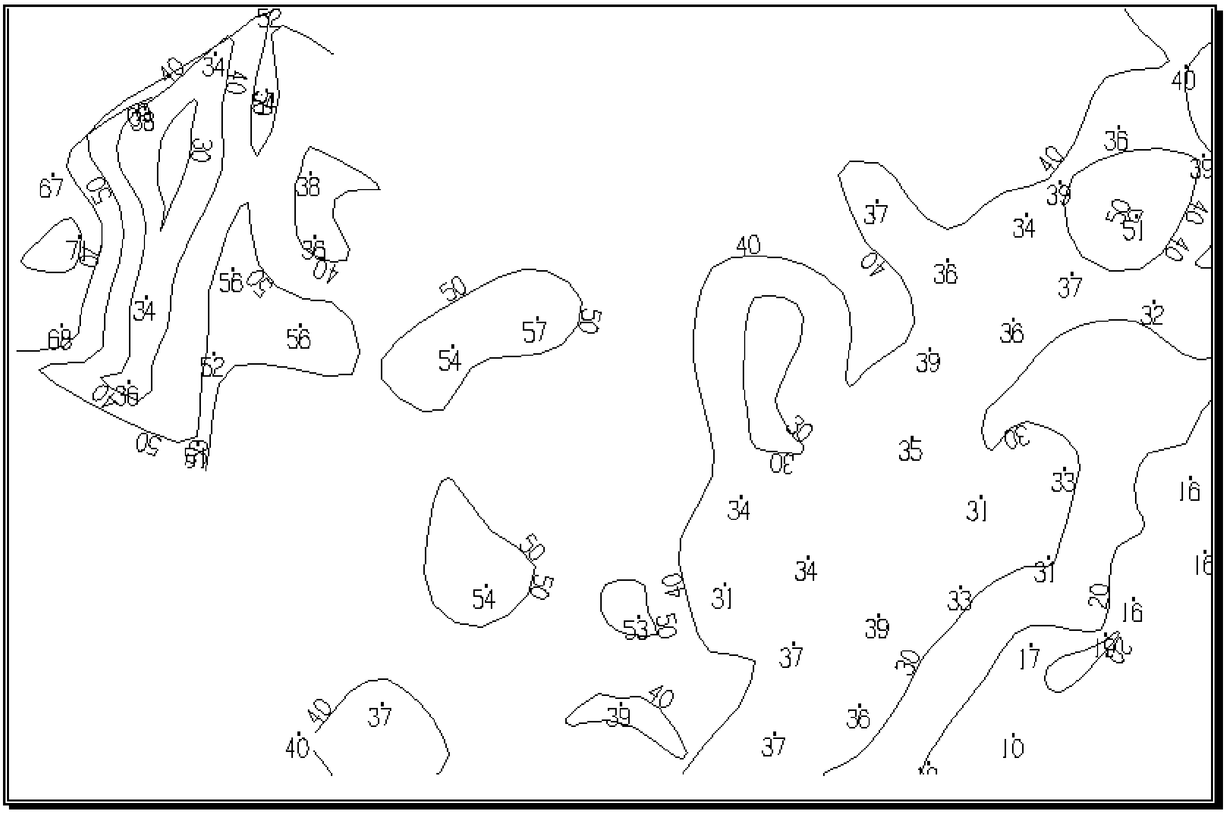

Figure 2: Example of Aquila Hardness Contouring

Dispatch System

As mentioned above, the Modular Mining Dispatch system monitors shovel, truck and drill productivity for both Highland Valley pits. The location of each piece of equipment is known at all times relative to fixed beacons in the pit with GPS gradually replacing this as machines are upgraded. One of the uses of such a system is to report (in real-time) on the movement of material - from shovel to truck to primary crusher - throughout the pit. Material is characterised by copper and molybdenum assays along with the Aquila hardness value.

Every ten minutes, Dispatch updates the record of how much material was dumped at each of the crushers along with its associated assay and hardness. The new ROM monitoring system is an extension of this by tracking the material from the primary crushers, through the conveyor network, onto the coarse ore stockpiles and into the mills.

Crusher/Conveyor Network

The flowsheet for the crusher/conveyor network ahead of the coarse ore stockpiles at Highland Valley is shown in Figure 3 below. The three crushers, two for Valley ore and one for Lornex ore, crush the material down below 150 mm before conveying it onto the stockpiles. The three stockpiles feed five grinding lines: stockpile #1 feeds D and E lines (both fully autogenous mills), stockpile #2 feeds A and B lines (both semi-autogenous mills) and stockpile #3 feeds C line (semi-autogenous, variable speed).

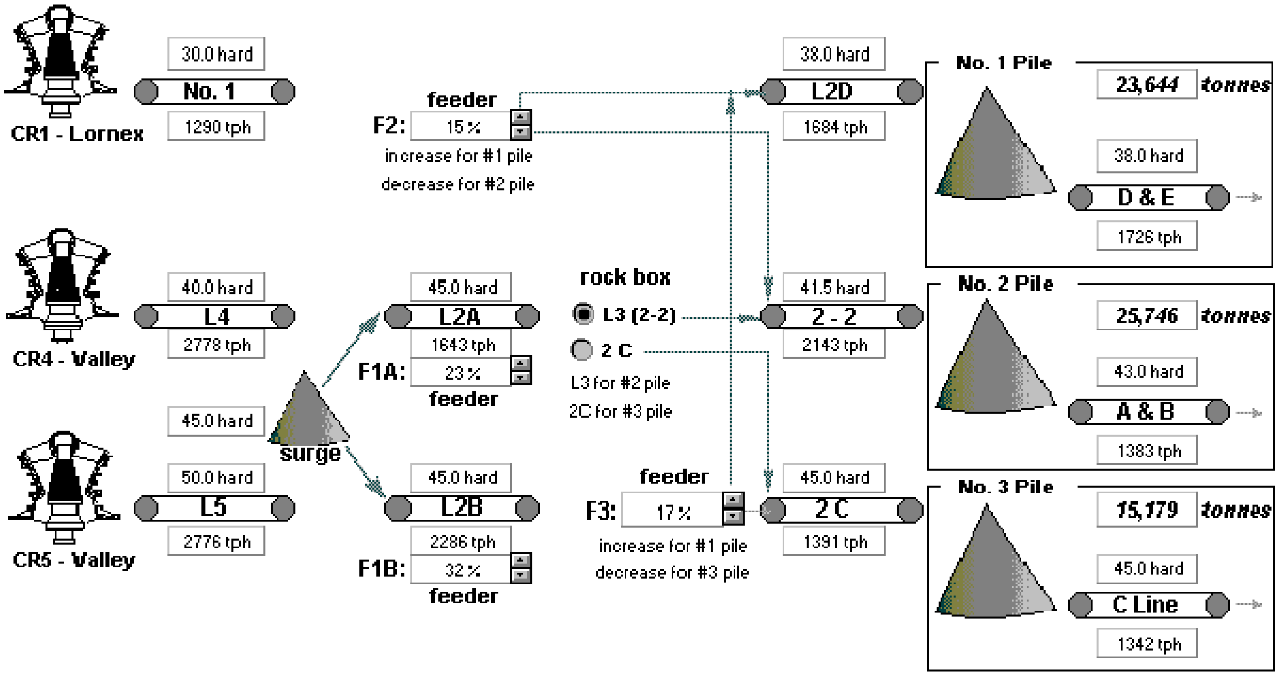

Figure 3: Primary Crusher/Conveyor Flowsheet

There is only limited scope for ore blending after the crushers. For example, crushed Lornex material can go to stockpile #1 and/or #2 (split via variable speed feeder #2). The presence of a small surge pile after the Valley pit crushers allows some cross-over between the two products but when both crushers are running at full capacity, there is little blending. Material from crusher 4 can report to either #2 or #3 pile (via the rock box flop gate). Material from crusher 5 can be split between #1 pile and #3 pile through variable speed feeder #3. The limited circuit options for blending are compounded by the size segregation that occurs at feeders #2 and #3. In both cases, the feeders send coarser material to #1 pile rather than to either #2 or #3 piles.

Stockpile Modelling

The crusher/conveyor network is well instrumented, with measurements of feeder speeds, splitter positions and a number of tonnages coming into the mill distributed control system. From this information, a material balance of the network can be calculated. The mass split for feeders #2 and #3 is calculated from an established feeder speed/throughput relationship. Changes to the flowsheet are typically through feeder speeds, splitter movements or equipment coming on/off line. The average conditions over the last minute are used to calculate the mass of material going to each stockpile. No time delays due to belt lengths are included as the distribution of material is more important than knowing exactly when it arrives at each pile. In a sense, it is a static simulation rather than a dynamic one (ie. “a slice in time”).

The coarse ore stockpiles and the surge pile after the Valley pit crushers are modelled as simple plug flow devices, composed of a series of fixed tonnage slices, each with an average hardness and assay. Figure 4 shows a schematic of the simple stockpile model.

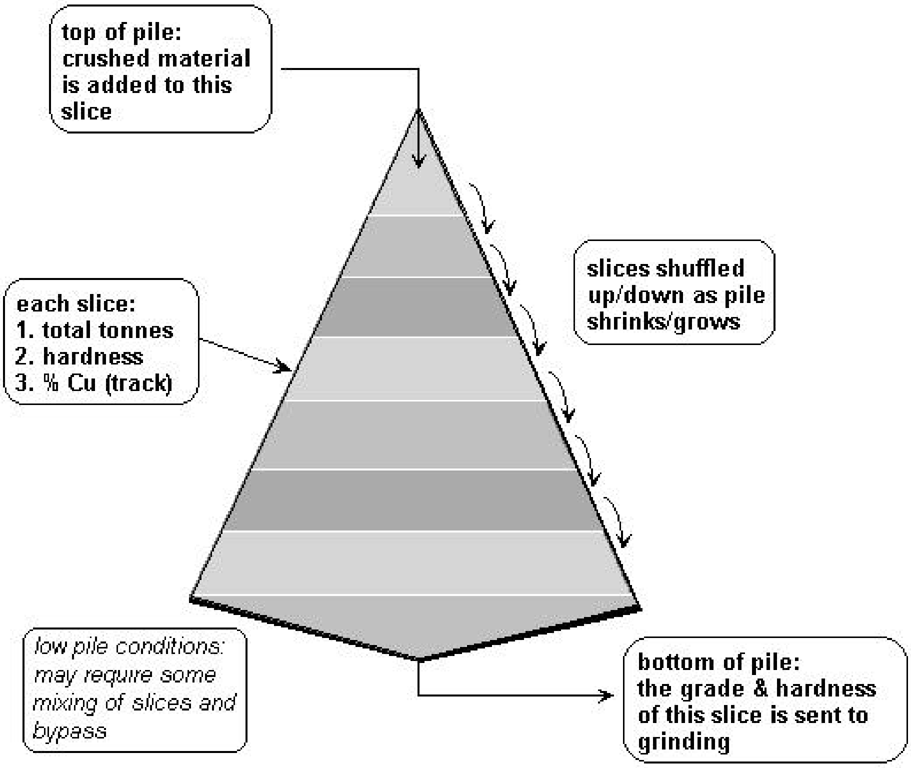

Figure 4: Schematic of Stockpile Model

Every minute, material from the conveyor network is added to the top slice while material reporting to grinding is removed from the bottom slice. The hardness and copper assay values for each slice are calculated as a weighted average of the material added/removed and the previous values. As the stockpile grows or shrinks, the slices are shuffled up or down the pile.

While the primary objective of this exercise is to estimate the ore hardness going to each mill, the copper assay values are also tracked as an indication of model accuracy. The predicted assays going to each mill can be compared with the on-stream analyser values for flotation feed (grinding circuit product). Trends in copper assays can then be used to monitor the residence time distribution of each stockpile. It is assumed that there is no hardness or assay segregation throughout the conveyor network and stockpiles. (Clearly not the case for particle size.)

While such a plug flow model should work when the stockpiles are high and well-formed, it is anticipated that a more complicated mixing model will be required for when the piles are low. Residence time studies and the use of copper assay as a tracking device will allow the mixing behaviour of each pile to be better defined in the future. However, the simpler plug flow model should be adequate for the majority of situations.

The average hardness, assay and total tonnage of each stockpile is displayed to the operator along with an estimate of the ore hardness reporting to each grinding line. This information allows the grinding operators to monitor changes in hardness and make changes when necessary.

ORE FRAGMENTATION

The other factor in ore variability is fragmentation or the mill feed particle size distribution. At Highland Valley Copper, the fluctuations in mill feed size outweigh ore hardness in terms of the effect on mill throughput. While there is significant variation in ore hardness throughout the two pits (as shown in Table 1), the dominant factor on the daily or hourly changes in mill tonnage is feed size. How do we know this? We measure it.

Measurement of ROM Size

In 1997, Highland Valley Copper installed an image analysis system to monitor the feed size distribution of the two autogenous grinding lines (D and E). Both lines are fed by the same stockpile. Video cameras were mounted at the transfer chutes ahead of each feed belt with two 500 W halogen lamps providing the controlled lighting conditions.

The signal from these cameras is transmitted to the WipFrag image analysis system by WipWare Inc. (Maerz, Palangio and Franklin, 1996). This PC-based system is capable of handling two camera inputs, however, HVC is presently upgrading the system to receive eight inputs.

The WipFrag software captures and digitises images of the falling material and isolates individual fragment boundaries (called the 'net overlay'). An example of a camera image and resulting overlay is shown in Figure 5.

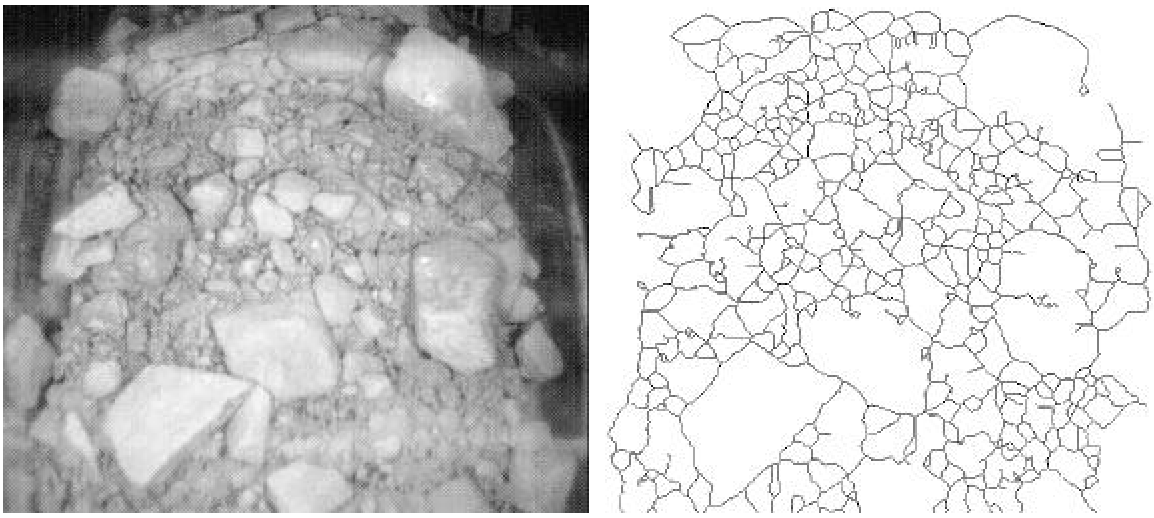

Figure 5: Example of Camera Image and WipFrag Net Overlay

Following the identification of boundaries, the fragment areas, volumes and masses are calculated before the size distribution by weight is determined. Like most image analysis systems available on the market today, the WipFrag system has difficulty resolving fine particles. This is dependent on the area being viewed and the image resolution (ie. pixels/m), as most systems are incapable of viewing particles below a few pixels in size.

The two most common problems encountered are the “fusion” of fines into one fragment and the “disintegration” of a fragment into two or more blocks.

There are methods to improve the resolution of fines, such as zooming in on a series of images and merging the data, but these are time consuming and usually require manual intervention. Under the current camera setup at HVC, it is believed that the WipFrag system can resolve particles down to approximately 15 mm. While this may not appear to adequately identify the fine “tail” of the distribution, this is smaller than the mill grate size and therefore can be grouped together (see *Coarse, Medium or Fine - What is Best?* below).

To compare the WipFrag size distributions with that determined by sieve analysis, a sample of material must be both screened and photographed and the two methods “calibrated” to each other. This involves curve-fitting and shifting the WipFrag distribution so that it matches the screen analysis.

At HVC, the WipFrag output is used as a control signal. That is, changes to the WipFrag distribution (both shape and size) are more important than how they compare with a “standard” sieve analysis. Although WipFrag may not produce an output comparable to screening, it has proven itself to be very repeatable. The dangers of losing data in “calibrating” a WipFrag distribution are very real and have been experienced at HVC. Consequently, as “raw” data as possible is used in the analysis of ROM fragmentation.

The WipFrag software currently processes twenty images per grinding line every five minutes and merges the data into a single result. The switching between the two lines is handled by WipFrag so that an update on each line occurs every ten minutes. The output is currently being logged to a file and contains the weight fraction in each of twenty size fractions (?2 geometric series).

As mentioned above, HVC is expanding the system to handle five cameras - one for each grinding line. WipFrag will automatically switch between lines after each image while the mill control system will perform the moving average calculations for the last twenty images. This will improve the update frequency without loss of accuracy due to an unrepresentative number of fragments being sampled.

An additional two cameras will be installed in the near future on the primary crusher products in the Valley pit. This will allow improved particle size control of the crushers which are integral to the fragmentation monitoring project (see *Primary Crusher Operation* below).

Effects of Feed Size on Mill Throughput

Autogenous and semi-autogenous grinding mills, by definition, are influenced by feed size as they use the rock for grinding media. The feed size becomes the rock charge and therefore, has a significant effect on the amount and type of breakage (ie. impact, attrition or abrasion).

The effect of feed size on mill performance is well documented in the literature both by operations (SME, 1985 pp 3C-83) and researchers (JKMRC, 1996 pp 178 - 180). It is generally agreed that a measure of feed size such as the 80% passing size is too crude to correlate to mill throughput. Instead, the shape of the distribution needs to be considered (eg. the slope of the cumulative distribution curve).

For fully autogenous mills, a sufficient amount of coarse material is required to act as grinding media while for SAG mills, a finer feed is preferred to increase tonnage. This is due to the fact that most SAG mills operate with a high ball charge that lessens the effect of feed size. The JKMRC (1996 pp 179) claim that, based on operational data, a ball charge above 5% by volume is the point where changing the feed size has a negligible effect on SAG mill performance.

Coarse, Medium or Fine - What is Best?

The WipFrag image analysis system has been monitoring the feed size distribution of the two autogenous mills at HVC since October 1997. Over this period, an enormous amount of data has been collected to correlate the effect of feed size on mill throughput. Although the two mills are fed from the same stockpile, differences in the feed size have been consistently measured by the WipFrag system.

Analysis of the data has shown that three size fractions have a significant effect on the autogenous mill throughput. These fractions approximately relate to the below grate size (-50 mm), above grate and below “coarse” size (50 to 125 mm) and above “coarse” (+125 mm). Figure 6 below shows the distribution of the three size fractions for a typical mill feed.

Note: these size fractions are measured by the WipFrag system and have been approximated to sizes as measured by sieving. These distributions can be compared to other WipFrag results with confidence however, comparison to screen analysis should be done with caution.

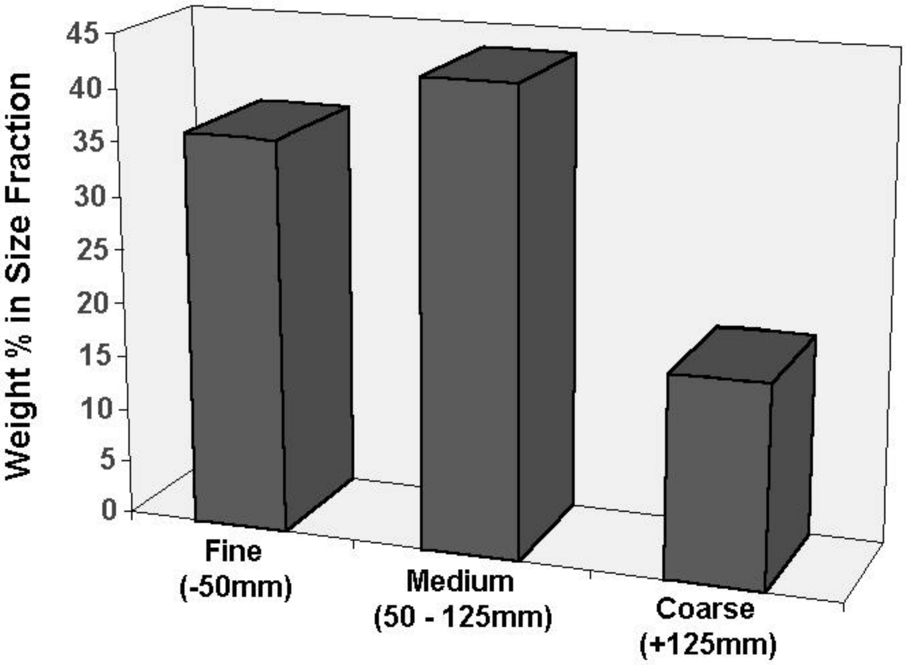

Figure 6: Typical Mill Feed Size Distribution

(Note: sizes as measured by WipFrag)

In general, both autogenous mills show increased tonnage with a greater amount of “fine” particles and a lesser amount of “medium” and “coarse” particles.

The effect of the fine fraction was expected as feeding below grate size material clearly will increase throughput, however, the influence of the coarse fractions contradicts popular opinion. The results from the WipFrag analysis showed that both autogenous mills preferred a finer feed (ie. less “coarse”).

A possible explanation is that the “medium” size fraction (as measured by WipFrag) is broad enough to contain both the grinding media as well as ‘critical size’ material or particles that are too small to assist in grinding and too large to exit the mill. The combination of these positive and negative influences results in a slightly negative correlation between the "medium" fraction and mill tonnage.

The "coarse" fraction contains particles that, although will act as media, wear down at a very slow rate and have a negative impact on throughput. In other words, there appears to be sufficient grinding media in the "medium" size fraction.

Although no continuous WipFrag analysis data are yet available for the SAG mills, preliminary studies have shown the these mills also prefer finer feed. Interestingly enough, the same WipFrag size classes are proving to be of significance. Once the permanent cameras on the remaining grinding lines are operational, the relationship between feed size and tonnage will be established for each mill.

Throughput/Feed Size Modelling

Based on the analysis described above, an equation predicting the change in mill tonnage with the three size fractions was developed. This equation revealed the magnitude of the feed size effects on autogenous mill throughput. Figure 7 is an example of the tonnage predictions for one of the mills over a 24 hour period.

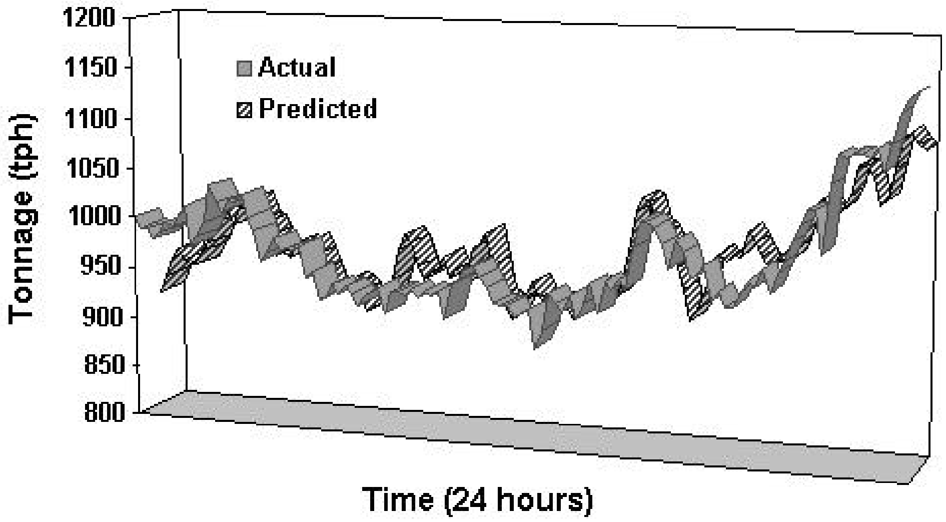

Figure 7: Example of Throughput/Feed Size Predictions

The data in Figure 7 shows that the mill tonnage varied from 900 tph to over 1150 tph with the equation predicting tonnage quite well. As the equation only considered changes in the three fractions, the close predictions show that the tonnage variations were entirely due to mill feed size.

The tracking of ROM hardness from the mine to each of the mills will complement the WipFrag analysis in the throughput/feed size modelling. The tracking system will provide an objective and inferential measurement of ore hardness than can be included in the model equation. The magnitude of the effects of the two ore properties on mill tonnage can then be monitored independently.

Primary Crusher Operation

The WipFrag system has also been used at HVC to assess the influence of primary crusher operation on mill feed size. It is well recognised in the industry that a gyratory crusher under choke feed conditions will produce more fines through inter-particle breakage than under non-choke conditions (JKMRC, 1996 pp 152). However, a primary crusher cannot dramatically alter the shape of the size distribution and overcome poor fragmentation. A primary crusher will generally only reduce the top size of the distribution; most or all of the “ultra fine” material (below WipFrag resolution) is generated through blasting.

WipFrag was used to compare the crusher product under choke and non-choke conditions. In both cases, the setting was maintained at approximately 152 mm while the crusher feeder speed was changed to keep the bowl full or empty. A number of choke/non-choke comparisons of product size were made with a typical result for the three fractions used in the throughput modelling shown in Figure 8 below.

As expected, the choke feed conditions produced a finer product, with particles in the “coarse” fraction (+125 mm) broken down into the “fine” fraction (-50 mm). The “medium” fraction (50 to 125 mm) showed little change.

Using the throughput/feed size equation developed for the autogenous mills, this difference in crusher product size was shown to produce a significant increase in tonnage. The side benefits of operating the crushers under choke feed conditions are more even mantle wear and longer liner life.

In the near future, cameras installed at the two Valley pit crushers will monitor the product and display the size measurement in the operator cab. The operator can then adjust the crusher setting to maintain the finest product possible without delaying trucks. Alternatively, a feedback control loop could perform this function automatically.

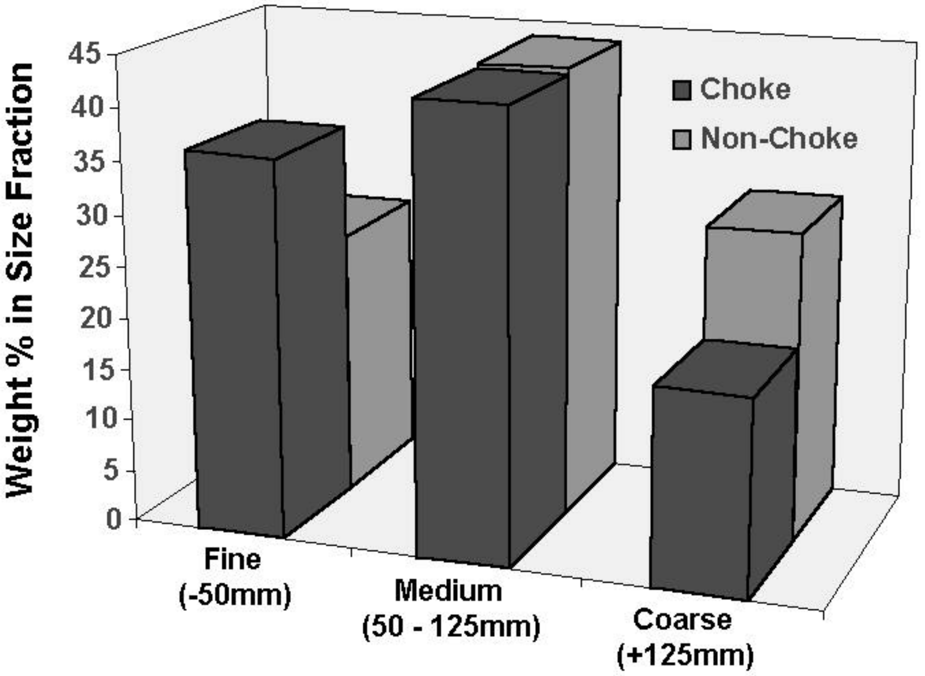

Figure 8: Effect of Primary Crusher Conditions on Mill Feed

(Note: sizes as measured by WipFrag)

BENEFITS OF ORE HARDNESS/SIZE MONITORING

The systems soon to be in place at Highland Valley Copper for tracking ROM ore properties and measuring feed size provide a continuous update of the hardness and size of the material going to each of the five mills. These systems utilise existing data communication networks and update themselves automatically - no additional paper work or manual data entry is necessary. They also provide the opportunity of assigning economic value to the benefits of ore blending, improved fragmentation and crusher operation through increased mill production.

Stockpile Blending

Currently, the blending of ROM material after the crushers is not optimised, with the conveyor network operated to maintain the three stockpile volumes as even and high as possible. There is no distinction of material based on its properties and therefore the stockpiles can vary significantly in hardness, grade and size.

Tracking the material hardness and assay will allow continuous reporting on the make-up of each of the stockpiles and provide guidelines for blending. No longer will the material being conveyed be simply “rock” but instead, has properties that need to be blended. Reporting on the quality of blending will identify areas for improvement as well as recognise when it has helped with production.

The option of automatically blending the stockpiles, based on a number of constraints and objectives, will be investigated at Highland Valley in the near future. Such a problem could be readily handled using a knowledge-based or expert system approach.

With WipFrag monitoring the crusher products, the added dimension of ROM size could possibly be tracked and used as another basis for stockpile blending. However, the well recognised - but poorly understood - size segregation in the feeders and stockpiles would make size modelling a very difficult task; something that would require more sophisticated methods than are currently used.

Improved Fragmentation

The first step in understanding the effects of fragmentation on mill throughput is through measurement and monitoring. The mill cannot confidently state what “optimum” feed size for each mill until we understand what we are currently receiving from the mine. In addition, the mill needs to recognise what changes can be made through crusher operation and blending to improve the ROM size distribution.

Monitoring fragmentation allows this ore property to become another measure of performance; as feed grade, recovery and throughput are now. By measuring the product of blasting as well as developing a closer definition of the mill’s requirements, a feedback mechanism can be established between the mill and the mine.

Finally, by quantifying the effects of fragmentation on mill production, a cost benefit analysis can be performed to determine the optimum degree of breakage in the mine. In other words, at what point does spending more money in the mine for better size reduction not have an increased benefit to Highland Valley Copper as a whole?

Monitor Process Performance

Mineral processing plants the world over are committing more resources to sophisticated control systems when in fact the main disturbance to any mill is feed variability. Better control over the feed material precludes the need for advanced control systems.

Not only are the feed changes variable in size, but variable in time (eg. “when will the ore change?”, “how long will the change last?”). By monitoring and recognising real ore changes, rather than ‘apparent’ ones, operators will gain a better understanding of process behaviour. They will develop cause/effect relationships that will grow into strategies of how to best deal with these changes. These strategies can then be programmed into automated control systems.

The identification of distinct ore types in terms of hardness and size will assist operators and control systems alike in establishing setpoints and optimising conditions.

Mill Feed Compensation

At Highland Valley Copper, four of the five grinding lines are affected - either positively or negatively - by segregation in the stockpiles. For example, WipFrag analysis of the two autogenous mills has shown a consistent difference in the two feed sizes. In addition, the difference slowly changes over time as the stockpile composition and volume varies.

It is possible, using a monitoring tool like WipFrag, to reduce the feed imbalance by changing the feeder ratios or how the stockpile is drawn down by the two lines. Experience at HVC has shown that, not only does every mill prefer a different feed size, but identical mills can be particular as well!

ACKNOWLEDGMENTS

The authors would like to thank Highland Valley Copper for permission to publish this paper and present the results contained therein.

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