THE VALUE OF DAILY HIT ORE HARDNESS TESTING OF SAG FEED AT THE MEADOWBANK GOLD MINE

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Abstract

In November 2017, Agnico Eagle Mines Limited (AEM) initiated a program to evaluate the value of routine ore hardness testing using semi-autogenous grinding (SAG) feed samples in forecasting the SAG Mill/Ball Mill (SAB) grinding circuit performance. Daily samples were collected over a two-month period and submitted for Hardness Index Tester (HIT) evaluation to provide estimates of the competency (Axb) and grindability (Bond ball mill work index [BMWi]). The statistical analysis of the ore hardness and WipFrag online sizing data suggest a strong correlation that confirmed the well-known expectation that feed size and hardness do affect the grinding performance, even in a secondary crushed feed situation. This means introducing routine HIT testing at site will enable the operations to maximize the throughput for a set grind target and verify if the grinding circuit is performing optimally for the actual feed, rather than feed predicted from mine planning and scheduling.

Keywords

Hardness, WipFrag, HIT, Bond, Meadowbank

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Introduction

The Meadowbank Mine is located in the Kivalliq region of Nunavut in Canada. The mine is owned by Agnico Eagle Mines Ltd. (AEM) and the nominal milling throughput to date is approximately 11000 tonnes per day (t/d). Figure 1 shows the geographical location of the mine, relative to Hudson Bay in Canada.

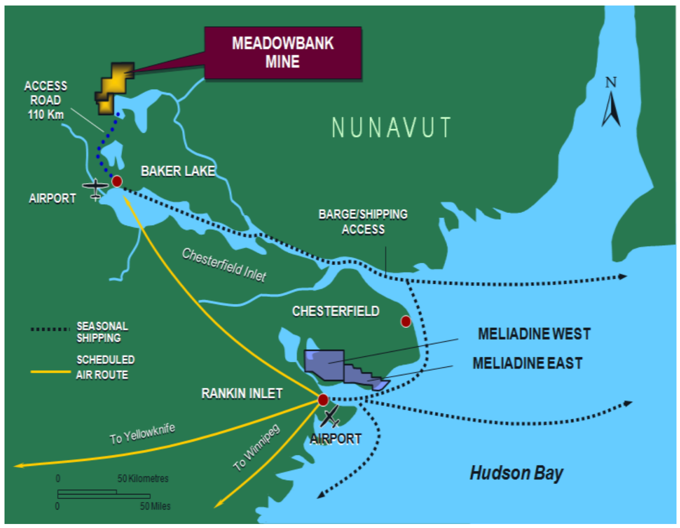

Figure 1 – Meadowbank Mine Location

AEM deployed the HIT device in August 2017 aiming to better understand the hardness variability of the Amaruq future ore to be processed at Meadowbank from mid-2019. The Amaruq deposit has a wide range of ore hardness, expected to be challenging in terms of the grinding circuit response. A geometallurgical hardness testing program, focusing on drill core samples, was initiated by AEM to model the spatial ore hardness variation from standard hardness test results (SMC Axb and Bond BMWi), supplemented with a higher number of HIT hardness test results. To demonstrate the capability of HIT results to predict mill performance, AEM initiated a focused evaluation at Meadowbank seeking to address the question, "Can routine ore hardness testing, using SAG feed samples, assist in forecasting the SAB grinding circuit performance?" In this paper, the authors describe the findings from the Meadowbank HIT evaluation program, targeting daily SAG feed samples from the mine, and processed at the AEM Technical Services metallurgical laboratory in the Abitibi region of Quebec.

Process Plant Description

Meadowbank has a two-stage grinding mill circuit (open circuit SAG + closed circuit ball mill), fed with secondary crushed ore from the mine with a F_{80} size of around 25 mm. The throughput capacity of the Meadowbank grinding circuit is 445 to 515 tonnes per hour (t/h) depending on ore type, at a final grind size P_{80} of 75 to 110 microns (µm). The main sections of the Meadowbank operations shown in Figure 2 are as follows:

- Crushing circuit – Primary gyratory crusher followed by double deck 6 ft x 20 ft screen, secondary cone crusher, in open circuit, feeding SAG feed stockpile.

- Grinding circuit – SAB circuit with a 7.92 m x 3.78 m 3550 kW SAG mill and 5.49 m x 8.84 m 4475 kW ball mill in closed circuit with 6 hydrocyclones (4 in use, 2 standby). Both mills are fixed speed. A portion of the cyclone underflow is diverted to feed a batch gravity concentrator, the remainder of the underflow reporting directly to the ball mill.
- Gold recovery circuit – Cyanidation and carbon in pulp (CIP).
- Sampling and analysis (S) – Thermo scientific SamStat-30 + PSM-400MPX particle size analyzer.

The process plant availability is 95% with a global gold recovery of 90.5% to 95.5% depending on the ore type.

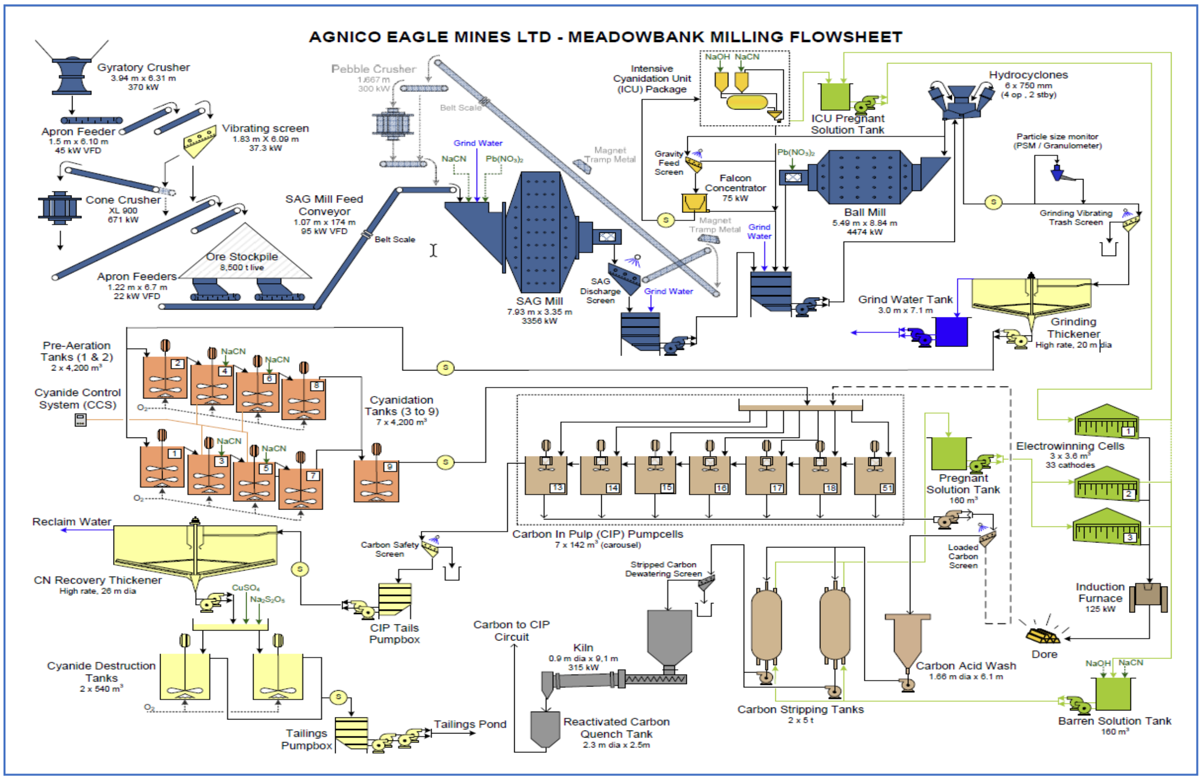

Figure 2 – Meadowbank Processing Flowsheet

The Meadowbank feed hardness is variable, being medium-hard to hard in competency, and medium-soft to medium-hard in grindability as per the summary in Table 1. The Bond BMWi results reflect a closing size of 75 µm. As the Meadowbank deposit is almost depleted, AEML is planning to open the Amaruq mine and process the ore in the Meadowbank plant as of mid-2019. In order to maximize recovery with the new deposit, a continuous gravity and concentrate regrind circuit is in the process of being installed.

Table 1 – Comparison of Meadowbank SAG feed ore properties

Ore Type	**SG (t/m^3)**	**Axb**	**Bond BMWi (kWh/mt)**
Goose	3.28	42.3	11.4
Portage	3.24	40.7	10.7
Portage E (Pushback)	3.40	29.3	11.3
Vault Main	2.78	37.6	14.0
Vault Porphyry	2.63	35.9	16.5
Amaruq	*2.72-3.15*	*24.9-51.4*	*13.7-16.2*

The above standard ore hardness results suggest the Vault ores are harder in crushing than Portage and Goose (P-G) ores, and significantly harder than P-G ores in terms of ball mill grindability. But Portage E (Pushback) ore is the hardest in terms of competency or crushing yet is still relatively soft in terms of grindability. The other finding worth noting is that Vault ore has a lower SG, which means the SAG mill would draw less power at the same filling, all else being equal. The ore parameters for Amaruq indicate the future mill feed will continue to be variable in hardness, especially in competency ranging from very hard to medium.

What is the HIT?

A new ore hardness testing device has been developed by SimSAGe Pty Ltd for rapid rock hardness determination, called the hardness index tester (HIT). The HIT exploits a central feature of single particle impact testing—that the Axb can be reliably estimated using one precise low energy test (Kojovic, 2016 and Napier-Munn et al., 1996). The HIT, for which a patent is currently pending, has been precision engineered to allow users to break narrowly sized fragments at a set specific energy, in a safe and easy manner.

The HIT device can be used to generate quantitative estimates of Axb and BMWi using relatively small samples of ore from the mine or mill feed. The HIT device allows operational, on the spot determination of rock hardness variability. It is hence ideal for routine testing of mill feed samples to monitor performance and adjust mill settings for optimum performance or geometallurgical program. Details of the HIT development and applications can be found in technical papers by Kojovic (2016) and Bergeron et al. (2017).

MAIN FEATURES OF THE HIT DEVICE

The HIT device was initially developed in 2013 for rapid low-cost Axb estimation, targeting small samples of fragments in the 15 mm to 20 mm size range. Figure 3 shows the second generation HIT prototype, which comprises a frame, a sample cup to hold the fragment to be crushed, crusher hammer assembly, and dual lever mechanism to trigger the release of the hammer onto the fragment in the cup. The sample cup sits in a dedicated grooved inset on the top surface of the frame base plate, and comprises a handle allowing a user to easily remove the sample cup from the frame during testing. The device is supplied with a novel quality assurance / quality control (QA/QC) feature to ensure that the targeted potential energy is consistently delivered. HIT users are provided access to online software for Axb and Bond BMWi calculations, eliminating the need to send the raw data offsite for analysis.

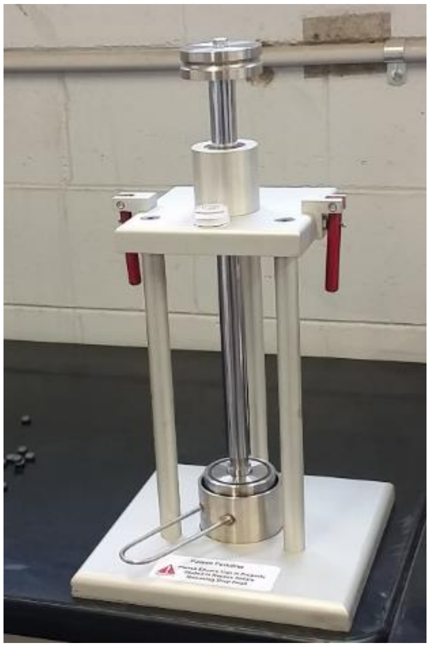

Figure 3 – Image of the HIT device (Prototype V2; Patent Pending 62/241,852, PCT/I B2016/001591)

Results from several industrial trials confirmed the HIT was able to align with the Axb derived using the JK drop weight test (JKDWT) or SAG mill comminution (SMC) tests, providing the same fragments were used in both test methods, including the initial fragment selection and product sizing protocol. If the selection and sizing protocols are not followed in the HIT testing, calibration against standard tests may be required. Figure 4 shows a recent comparison using drill core samples from a copper deposit in Canada, highlighting a consistent correlation between the SMC and HIT Axb results across a wide range of hardness (Axb 30 to 120).

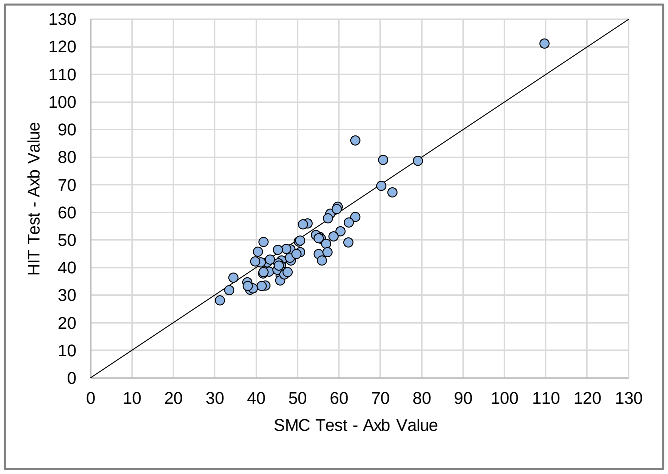

Figure 4 – Comparison of SMC Axb Values and Corresponding HIT Axb Proxy Estimates (62 drill core samples)

The industrial trials also demonstrated the possibility of using HIT for Bond BMWi estimation via a calibration between the breakage response at high specific energies and actual full Bond BMWi results on the same ore. This concept is based on historical work, including the studies in coal breakage linking the slope and intercept of the Rosin-Rammler curve to the coal hardness. As the specific energy required in the HIT testing is of the same order as that delivered during one cycle in the Bond BMWi laboratory mill, the fragment size for the HIT BMWi proxy tests is around 8 mm to 10 mm. Results from industrial trials with over 100 samples covering eight ore deposits suggests that this approach can be used to estimate the Bond BMWi within an acceptable uncertainty for GeoMet applications. Figure 5 shows a recent example with an average relative error better than 5%.

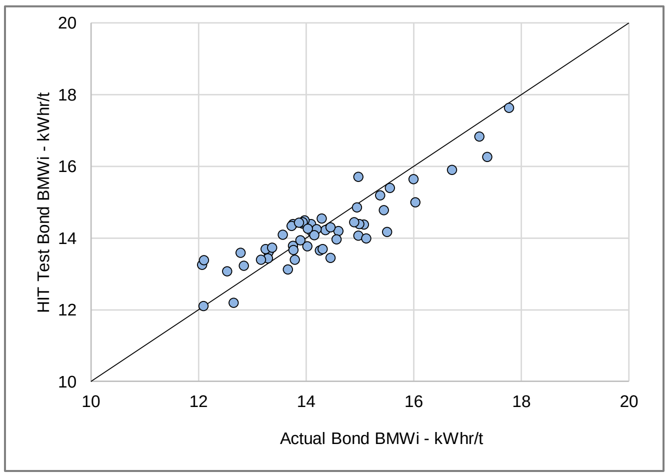

Figure 5 – Comparison of Estimated and Measured Bond BMWi Results (62 drill core samples)

The good consistency between the HIT results and standard DWT/SMC and Bond BMWi laboratory test results, described in Bergeron et al. (2017), gave confidence to AEML to initiate the evaluation of the HIT at Meadowbank as a practical application in forecasting the Meadowbank mill performance as described below.

HIT Evaluation at Meadowbank

The HIT evaluation program at Meadowbank was initiated by AEM in November 2017 to demonstrate the capability of HIT hardness results to predict the mill performance. Knowing that the mill is fed with a relatively fine SAG feed, it was not clear if routine ore hardness testing using the HIT device could assist in forecasting the SAB grinding circuit performance.

AEML commenced HIT testing of selected fractions from SAG mill feed samples collected daily at Meadowbank. A daily sample of approximately 10 kg was collected from the apron feeder since October 7, 2017. The samples were sent to the AEML's Technical Services laboratory for size analysis and HIT testing (triplicate tests using the Axb proxy protocol on ten 22.4 mm x 19 mm fragments, and duplicate tests using the Bond BMWi proxy protocol on twenty 11.2 mm x 9.5 mm fragments). AEML also included SG determination using a pycnometer on a separate split of 11.2 mm x 9.5 mm fragments. Meadowbank provided daily production operating information for each day sampling was conducted, including WipFrag sizing data. The initial set of data reflect 55 days of operation, from October 7 to November 30, 2017. The HIT evaluation program was extended until end of March 2018, with a further 107 days of sampling.

In parallel to the Meadowbank HIT evaluation program, AEML had also initiated a geometallurgical program for the Amaruq open pit mine, including hardness characterization using standard tests supplemented with a greater density of HIT tests. AEML expects to have its first geometallurgical 3D block model related to Amaruq rock hardness by mid-2019 and an optimized model in the third quarter of 2019. Figure 6 shows the relative location and main geological ore types of the two deposits. The HIT testing to date suggests the ore is harder in the east, compared to the ore from the west extremity, and a strong correlation of Axb with lithology, which makes the spatial interpretation simpler. However, the BWi is less dependant on the lithology. This will be the first time HIT testing will have been used to help build a geometallurgical model for hardness, potentially enabling AEM to modify the mining plan to consider hardness in the life-of-mine (Bergeron, 2018).

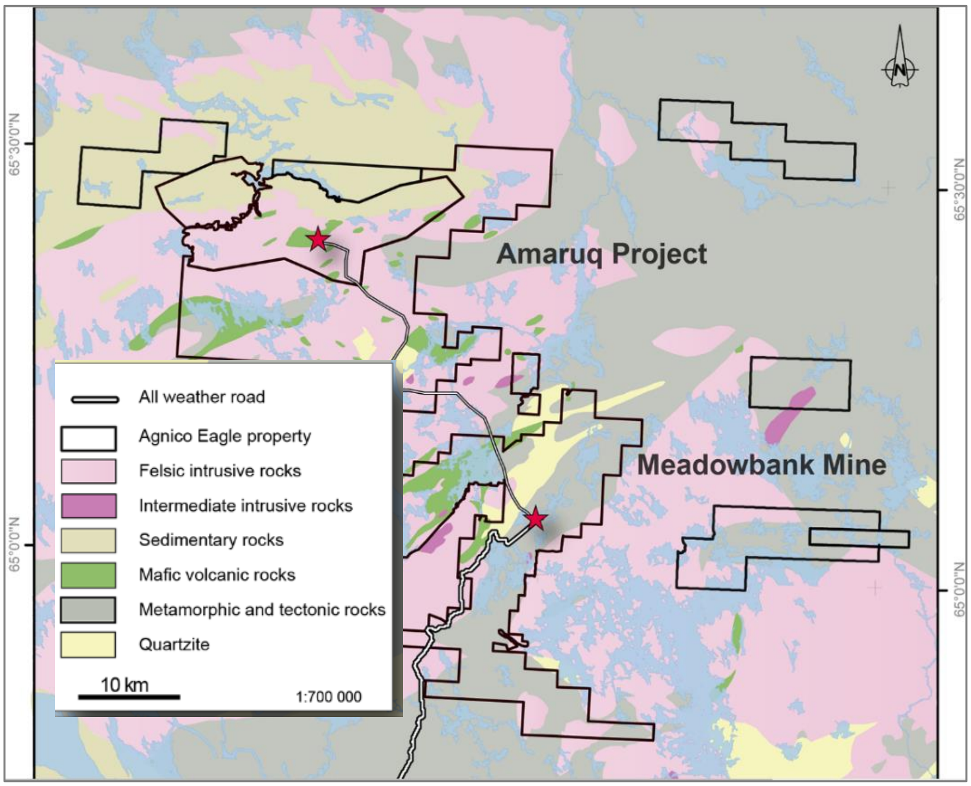

Figure 6 – Amaruq and Meadowbank Deposit Locations and Geology

Data Analysis Approach

AEM provided a summary of the triplicate HIT Axb and duplicate HIT Bond BMWi results in Excel, together with the operating information for Meadowbank. The latter included daily averages for the following variables as shown in Table 2.

Table 2 – Operating Variables (daily basis)

Operation	Feed and Product Size	Performance
Ore zone vault (%)	SAG F_{80} (inch) WipFrag	Throughput (t/h)
Crusher shut down (h)	SAG %-1 inch WipFrag	Tonnage (t/d)
Mill down time (h)	SAG T80 (when available)	SAG power draw (kW)
Availability (%)	Product P_{80} (cyclone OF)	Ball mill power draw (kW)

Some of the main challenges anticipated in the HIT evaluation program included the following:

- HIT testing and feed sizing were conducted on material from a ~10 kg sample of SAG feed (mix of grab samples and composites). This approach meant the sampling was not likely to be representative of the SAG feed.
- Manual sampling of coarse material is challenging, despite the fine feed size (low F_{80}).
- Operating data reflect the daily average performance/statistics, which may not align with the feed sample collected for HIT testing and size analysis.
- Daily performance may not reflect the optimum/maximum performance, for example, packing issues in the SAG due to new lifter liners or downstream restrictions.
- HIT Bond BMWi estimates are derived from a default calibration model, which may need to be updated to more accurately reflect the grindability of Meadowbank ore types—this appears unnecessary based on a small subset of monthly composite samples submitted for full Bond testing.

The comparison of the SAG feed size F_{80} determined from the apron feeder samples with the WipFrag results is shown in Figure 7. There are times the spot sampling mirrors the WipFrag trend, but generally cannot be regarded as a reliable measurement of the average feed size treated by the mill. The comparison also highlights the tendency of the apron feeder sample to be coarser than the average feed size, depending on when the sample was taken.

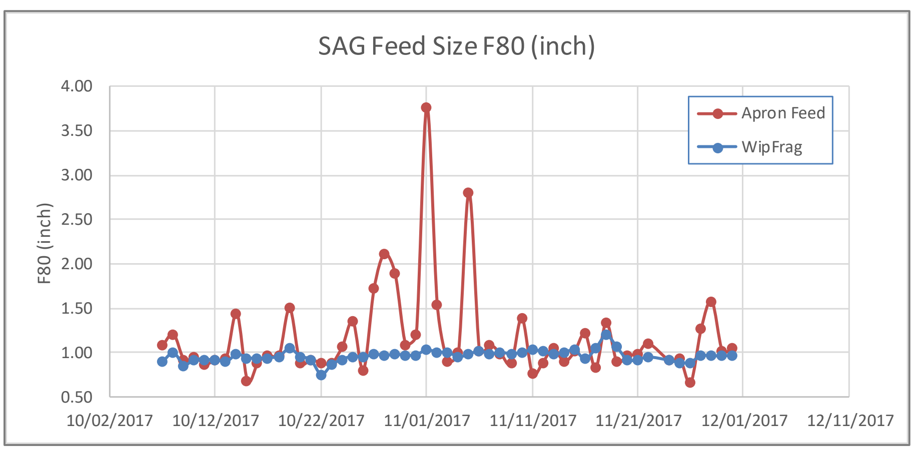

Figure 7 – Comparison of SAG Feed Size F_{80}, Apron Feeder Spot Sample, and WipFrag Daily Average

The modelling comprised separate least-squares linear regression analysis of the SAG and ball mill performance, represented by the SAG specific energy (SE) (kWh/t) and grind size P_{80} (µm), respectively. The regression considered both HIT hardness parameters and operating variables expected to affect the mill performance, including the following:

- Crusher shut down (hours)
- % -1 inch (SAG feed)
- Ore SG (calculated from % Vault, assuming two ore types, Portage 3.24 t/m^3 and Vault 2.70 t/m^3)
- SAG SE (kWh/t) – used only in the ball mill circuit P_{80} regression model
- Ball mill power (kW) – ball mill circuit only.

The ore hardness parameters HIT Axb and HIT Bond BMWi were used, as well as the standard deviation (SD) for each, reflecting the variability measured for each apron feed sample. For the HIT Axb, the actual term used in the regression was 100/Axb, which has the units of kWh/t, better reflecting the ore hardness in terms of grinding.

Initial Modelling Results

The regression analysis confirmed the well-known expectation that feed size and hardness affect the SAB grinding performance. The strong correlations for both the SAG SE and P_{80} indicated a relative error lower than the assumed experimental uncertainty of 5%. These results are very encouraging, despite the expected difficulties in relating the hardness of spot samples with daily performance. The best fit models had the following form:

$$SE = f(Axb, SD_{Axb}, BMWi, SG, \%\text{-}1\ inch) \quad (1)$$

$$P_{80} = f(BMWi, SD_{BMWI}, Axb, SG, \%\text{-}1\ inch, BMKW, SE) \quad (2)$$

where SE = SAG SE kWh/t
Axb = HIT Proxy Axb
BMWi = HIT Proxy Bond Wi (kWh/t)
SDAxb = SD of HIT proxy Axb (triplicates)
SDBMWi = SD of HIT proxy Bond Wi (duplicates)
SG = Specific gravity of ore, calculated from %Vault (SG = %v x 2.7 + (1-%v) x 3.24)
% -1 inch = WipFrag percent finer than 1 inch
BMKW = Ball mill power draw (kW)

The above expressions can be re-arranged to allow AEML to fix the P_{80} (on the Meadowbank target) and predict the mill throughput to identify whether the circuit is underperforming.

One interesting observation from the modelling was the suggestion that both Axb and BMWi affect the SAG performance. This is not surprising since the Meadowbank feed is relatively fine and the SAG mill would behave more like a ball mill, where the grindability is an important variable. A higher SG, reflecting more Portage ore, would not only be softer but also draw more power per cubic metre of ore in the mill.

The fact that Axb appeared significant in the ball mill performance model was probably related to the dependence of the ball mill grinding circuit on the SAG mill circuit behaviour. If the ore is hard and competent, the SAG mill can still bypass the finely crushed material to the ball mill circuit, which would put extra load on the ball mill circuit. As expected, increasing the ore hardness or percentage of -1 inch in the SAG feed raises the P_{80}, whereas increasing the SAG SE, SG, or ball mill power should reduce the P_{80}. The calculated and actual SAG SE and ball mill P_{80} trends over the period covered in the regression analysis are shown in Figure 8 and Figure 9 (gaps reflect missing inputs for the model calculation).

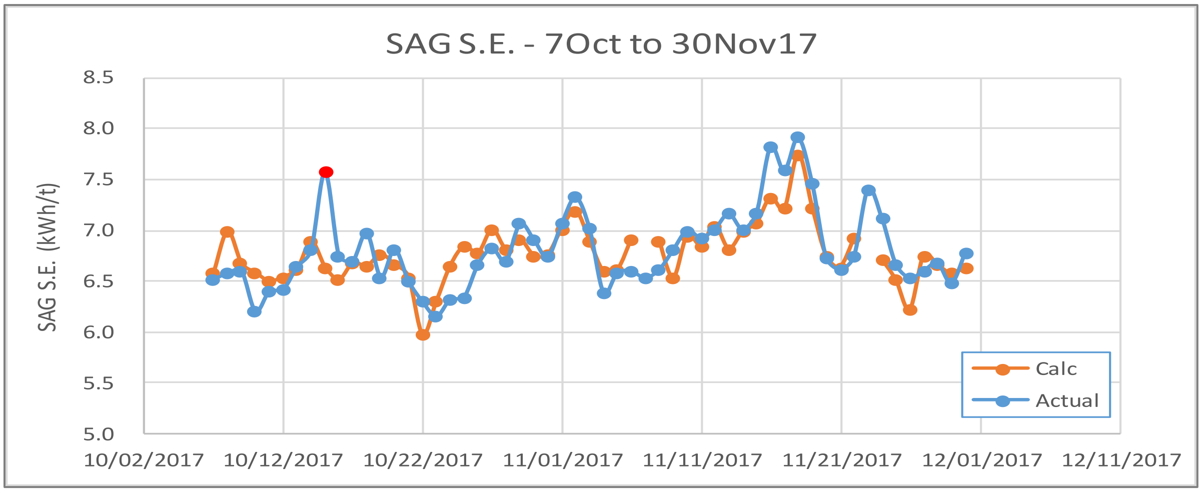

Figure 8 – Trend Showing Actual and Calculated SAG Specific Energy for the Initial Trial Period

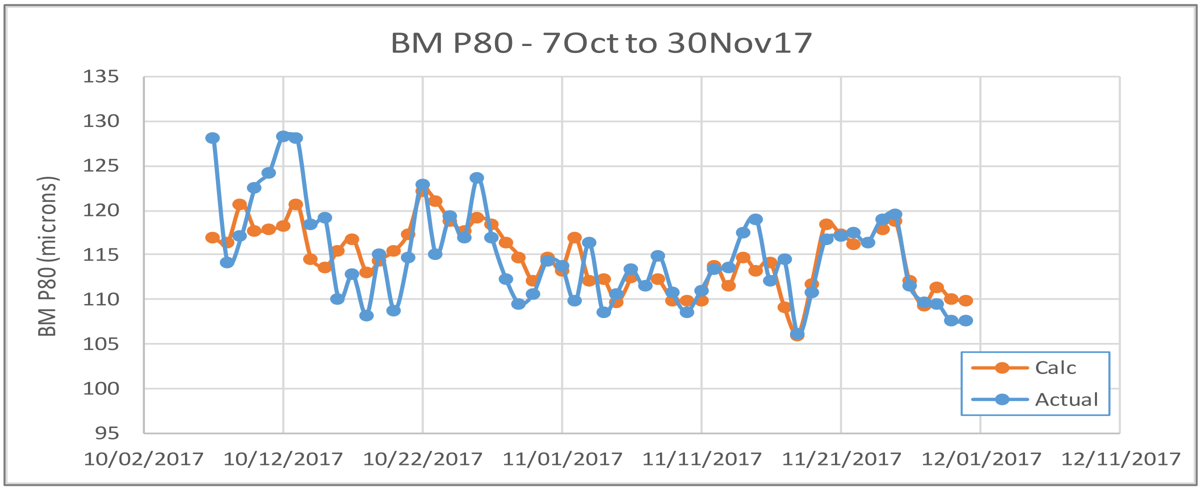

Figure 9 – Trend Showing Actual and Calculated Ball Mill Cyclone Overflow P_{80} for the Initial Trial Period

Both the SE and P_{80} models show room for improvement, suggesting that the measurement of ore hardness from one spot sample each day may not be representative enough of the overall ore hardness treated each day. Hence there may be merit in collecting a composite sample each day to get a better representation of the feed ore treated each day.

Validation Results

The HIT evaluation program was extended until the end of March 2018, generating a further 107 days of sampling. This additional period provided an ideal data set for model validation. To this end, the model developed from initial 53 days of monitoring was used to forecast performance for the remaining 107 days not used in model calibration. This approach was considered a textbook example of empirical model validation (Kojovic and Whiten, 1994). The calculated and actual SAG SE and ball mill P_{80} trends over the periods covered in the regression analysis and validation are shown in Figure 10 and Figure 11.

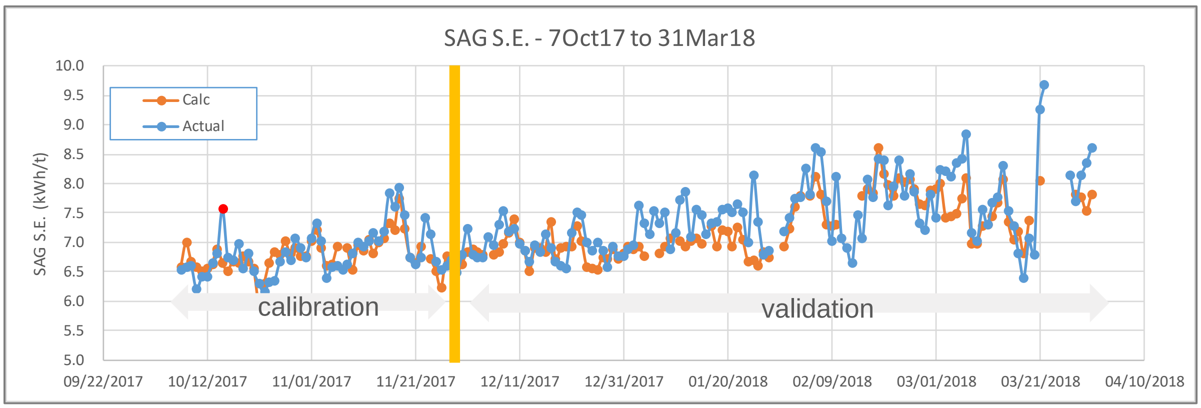

Figure 10 – Trend showing Actual and Calculated SAG Specific Energy for the Initial Trial and Forecast Periods

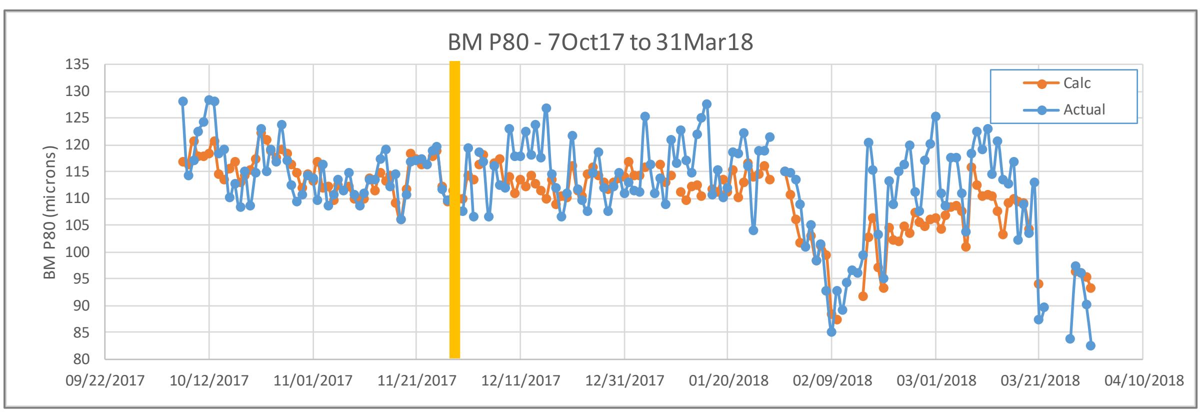

Figure 11 – Trend showing Actual and Calculated BM Cyclone Overflow P_{80} for Initial Trial and Validation Periods

The agreement between the model and forecast performance in Figure 10 and Figure 11 is clearly not as accurate as the calibration, but still within a 5% relative error. These results are very encouraging, with the model tracking a major change in SAG SE and BM P_{80} in mid-February 2018 when the tonnage was significantly reduced. Hence the model can be used by AEML to help identify whether the circuit is underperforming.

Hence the model based on results from daily HIT testing, combined with key inputs from WipFrag, offers a useful tool to 1) verify the actual t/h versus the predicted value as a measure of the circuit efficiency, and 2) justify the circuit performance when faced with different feed types. Validation using plant performance data around the time of sampling was shown to improve the model accuracy, as expected.

Meadowbank decided to extend HIT evaluation until end of 2018, providing an even larger data set for validation. The model highlighted significant discrepancies between the observed and forecasted performance (SAG SE and BM Cyclone overflow P_{80}), prompting a lengthy investigation into the cause. Meadowbank did confirm that the issues were related to the reliability of the SAG feed conveyor camera and not any other external factors (Leetmaa, 2019). As such, Meadowbank will follow up on the camera issues and then plan a new phase of SAG feed HIT monitoring to validate the performance model (Equations 1 and 2).

Conclusions

The Meadowbank HIT evaluation is the first of its kind and has illustrated the key issues in attempting to use the HIT as a routine SAG feed hardness tester. One of the most significant challenges is sampling, as the daily average mill performance may not align with the hardness of the mill feed spot sample collected for HIT evaluation.

The observed variation in Axb was found to be more significant than Bond BMWi, 27 to 45 for Axb and 12.9 kWh/t to 15.4 kWh/t for Bond BMWi. These results align with the range of standard JKDWT/SMC and Bond BMWi test results on samples from the Meadowbank deposit.

The observed variation in the grinding circuit performance was found to be strongly correlated with the HIT ore hardness parameters. Other variables affecting the SAG and ball mill circuit performance are the feed size, specifically the % -1 inch, and ore SG as expected. The data from the HIT testing was able to explain the throughput issues in Q1 2018.

Meadowbank has expressed a need to re-work equations 1 and 2 to predict the throughput (t/h) for a given target grind size (P_{80}). This approach would allow Meadowbank to:

- Verify if the grinding circuit is performing optimally, and
- Maximizes the throughput for a set target grind size.

Having successfully demonstrated the capability of the HIT results in predicting mill performance, AEML plans to continue using the HIT test to map the hardness variation in the future Amaruq deposit and develop an ore blending strategy based on the results.

The ability to reliably determine the hardness of the feed ore to be presented to the mill using the HIT device presents a simple opportunity for improving the efficiency of any operation, at an acceptable cost.

Acknowledgements

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