TENTH ANNIVERSARY OF SAGDESIGN TESTING PRODUCTION SUCCESSES AND DEVELOPMENT

*J.H. Starkey[1], J.J. Hedderson[1] and S.W. Reeves[1], and M. Brissette[2]

[1]*STARKEY & ASSOCIATES INC.*
212-151 Randall Street
Oakville, ON, Canada L6J 1P5
*(*Corresponding author: john.starkey@sagdesign.com)*

[2]*COREM*
1180 Rue de la Minéralogie
Quebec, QC, Canada G1N 1X7

ABSTRACT

Starkey & Associates Inc. (S&A) are celebrating the 10th anniversary of SAGDesign testing and methodology, with over 1,000 tests performed to date on 179 mining projects. These tests were done to size SAG and ball mills in compliance with the requirements of mining project studies. The test has become standard in Russia, and for large companies such as ArcelorMittal, Agnico-Eagle, FLSmidth, and Hudbay Minerals.

This paper presents the updated SAGDesign database, its use to achieve successful start-ups, and introduces the details of the recent SAGDesign based developments for geometallurgical testing, of the SAG Variability Test (SVT) and the Bond Variability Test (BVT).

KEYWORDS

SAGDesign, SAG Mill, Ball Mill, Mill Design, Geometallurgy, SVT, BVT, Comminution Design

List of Acronyms

Acronym	Full Name
SDT	SAGDesign Test
SVT	SAG Variability Test
BVT	Bond Variability Test

List of Defined Terms

Term	Unit	Definition
F80	mm	80th percentile of the mill feed cumulative particle size distribution
T80	mm, µ	80th percentile of the ball mill circuit feed stream cum particle size dist.
P80	microns	80th percentile of the mill product cumulative particle size distribution
W_{SDT}	kWh/t	The specific energy to grind 1 tonne of ore from F80 152.4 mm to P80 1.7 mm in a SAG mill, as measured by an SDT
W_{SVT}	kWh/t	The specific energy to grind 1 tonne of ore from F80 152.4 mm to P80 1.7 mm in a SAG mill, as modeled by an SVT
S_d-BWI	kWh/t	The work index resulting from a Bond Ball Mill Test on SAG ground ore

INTRODUCTION

The effort to create an accurate SAG mill test for mill designs began 26 years ago in 1989 when the principal author started independent practice as a Consulting Engineer. At that time, the only methods available to design SAG mills involved the use of private intellectual properties, and the hiring of firms who provided the expertise associated with those technologies. It is the opinion S&A that a mining or engineering company should not delegate this important work of designing grinding mills to others unless they choose not to have skilled mill designers on staff. In this case, delegation to independent consultants is recommended.

The benefit of open technology has been proven based on the logic and good documentation of the Bond Ball Mill Work Index testing presented to the mining industry in the 1950s by Allis-Chalmers through the well published works of Fred Bond. The same openness is required for SAG milling. Every client should have a process engineer able to understand the final design methodology and assumptions to check the grinding mill selections independently thus mitigating the risk. This would allow clients to evaluate the mill sizing, costing, and ore production forecasting for grinding mills prior to signing a recommendation or purchase order on behalf of their shareholders/owners to buy a grinding mill, which accounts for a significant portion of the process plant equipment capital costs. Unfortunately, grinding designs that fail to achieve design tonnage have occurred recently in the industry and now have raised public concerns that SAG mills are automatically an inherent risk to the mining project. When properly used, SAG and AG technology can be very cost effective in terms of both capital and operating costs. When improperly used and required grinding capacity is not provided, financial consequences follow. While modifications can usually be added to correct design problems, the time value of invested capital during first year of operation (the payback period) is so high that the purchase of proper equipment before start up is essential to a successful start-up. The retrofitting of comminution equipment, particularly SAG mills, after start-up can be costly (in excess of CAN$50 million from news releases) and must be avoided in the future for the good will of investors and clients. On the other hand, successful plant start-ups and expansions are occurring when the mills were properly sized according to the measured ore hardness as it relates to the mine plan.

The significance of the 10 years of SAGDesign testing described in this paper, is therefore to define and prove that a mill design method has been introduced which allows plants to achieve design production from the start of operations. This paper explains and documents the history of the use of SAGDesign technology as recorded in the SAGDesign Test database and in example start-up applications.

SAGDESIGN TEST DATABASE

The SAGDesign database was first published in 2009 (Starkey & Samuels, 2009) and since then has more than quadrupled from 232 to over 1000 samples tested on 179 mining projects. These graphs, in the same format as before, are given below.

Figure 1 below shows the SAG grindability results from each SAGDesign test. W_{SDT} is defined as is the SAG pinion energy to grind a primary crushed ore from F_{80} 152 mm to an 80% passing transfer size of 1.7 mm. From the database used to create this graph, it is seen that the average SAG hardness is 9.0 kWh/t, the 80^{th} percentile value is 12.4 kWh/t, while the maximum SAG hardness is 34.9 and the minimum is 0.2 kWh/t. The extreme variability of SAG hardness is the reason why the W_{SDT} value for every relevant sample in an ore body must be accurately measured as part of the grinding mill design process.

Figure 2 shows the SAG Discharge Bond Work Index results from each SAGDesign test. Here the Bond Ball Mill Work Index is specifically defined (and measured) as the S_d-BWI in kWh/t, and is the Bond BM Wi value of SAG ground ore taken from the SAG mill discharge of the SAGDesign test. From the data used to create this graph, it is seen that the average S_d-BWI is 14.7 kWh/t, the 80^{th} percentile value is 17.4 kWh/t, while the maximum S_d-BWI is 26.2 and the minimum is 4.4 kWh/t.

The NICO Project is highlighted because of the properties of that ore which are unique in the database. The ore was identified through SAGDesign testing as being exceptionally hard to grind in the SAG mill but only of average hardness in a ball mill, as measured by a Bond Ball Work Index test performed on the SAG ground ore (Starkey & Samuels, 2010). Ultimately, this extreme SAG specific grinding energy of over 30 kWh/t, which can be clearly seen in Figure 1, led to the rejection of SAG milling technology at that stage of the study. Since the NICO project has not moved forward at this time, the value of this information for this paper, is to confirm the ability of the SAGDesign test to measure SAG hardness at any level, especially for hard ore, and early enough in the project development cycle to avoid mill sizing mistakes.

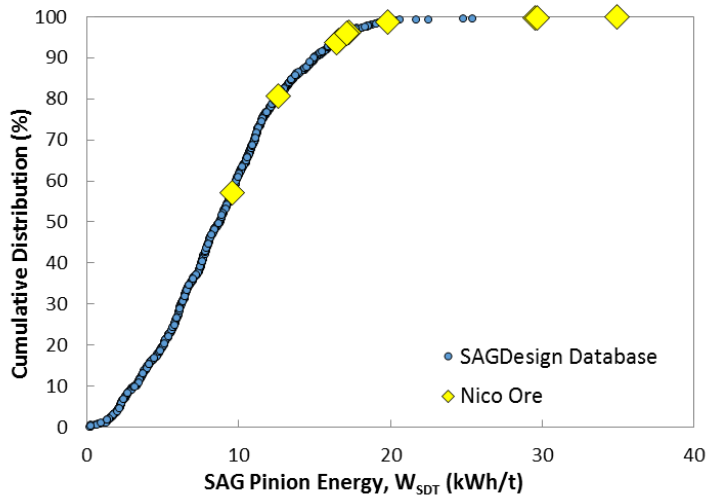

Figure 1 – SAGDesign Database: SAG Test Results, SAG Pinion Energy (W_{SDT}) Vs Dist. %.

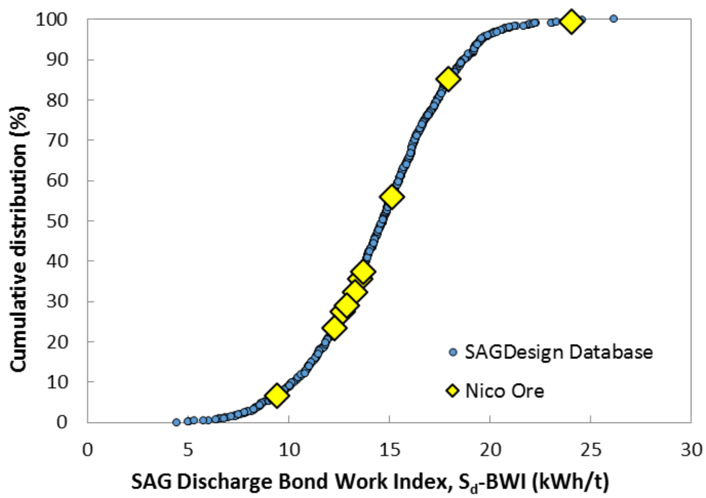

Figure 2 – SAGDesign Database: SAG Discharge Bond Results, S_d-BWI Vs Dist. %

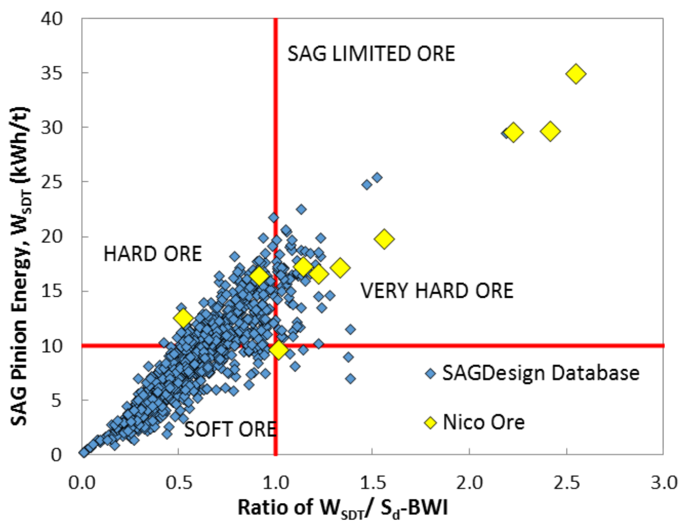

Figure 3 – Ratio of W_{SDT}/S_d-BWI Plotted Against SAG Pinion Energy or W_{SDT}

Figure 3 is used to classify ores by comparing the SAG hardness with the SAG Discharge Bond BM Wi as a calculated ratio of these hardnesses, plotted against the measured SAG Pinion Energy. The figure is divided into four quadrants, three of which are well populated, generally defined as soft, hard and very hard ores. Very hard ores are qualified by a W_{SDT}/S_d-BWI ratio greater than one. While these two values are both in kWh/t, W_{SDT} is the specific SAG grinding energy and S_d-BWI is the work index only. As a result, the ratio can only be used as a convenient factor to compare one sample with another. This information is instructive when selecting the comminution flowsheet, including the relative distribution of power between SAG and ball mills, and the use of pebble crushing.

It has been shown that the use of pebble crushers will typically improve the energy efficiency of overall size reduction, but the benefit realized is generally related to the availability of competent pebbles in the mill discharge and therefore to the measured SAG hardness. When the ore is soft (bottom left quadrant), a pebble crusher is not recommended for ores less than 5 kWh/t (W_{SDT}). However, a pebble crusher is optional to achieve design throughput in the medium range of 5 to 10 kWh/t for W_{SDT}. Serious consideration to use a pebble crusher should be given to ores in the top left quadrant. For ores with a ratio of W_{SDT}/S_d-BWI over 1 shown in the top right quadrant, a pebble crusher should always be used.

A possible exception to this classification method for flowsheet selection is when a future expansion is incorporated into the design. In those cases, the pebble crusher can become part of the expansion flowsheet. If so, it can make a dramatic difference particularly when the ore becomes harder over the life of mine.

Average specific gravity for the database samples was 2.99 g/cc and ranged from 2.36 to 4.73 g/cc. This data is recorded as SAGDesign tests are performed on a volumetric charge of ore and are corrected to a final result of kWh/t by using the measured specific gravity in the calibration equation. This allows for this methodology to be used with confidence on a variety of ore types, from soft and dense iron oxide ores, to hard and light gold bearing silicate ores. S&A confirms that since SAGDesign testing was introduced in 2004, the calibration equation to calculate W_{SDT}, kWh/t from test results has not changed.

ADDITION OF GEOMETALLURGICAL TESTING

More recently, the SAG and Bond tests within the SAGDesign test were shortened to 3 cycles each by first studying and using the SAGDesign database. The resulting tests are modeled to calculate a prediction of the equivalent SAGDesign test results suitable for use in geometallurgical applications. By doing this, 95% of the SAG database was shown to have a relative error of less than 15%, averaging 5.5%, for the SAG Variability Test (SVT) and 98% of the Bond database was shown to have a relative error of less than 15%, averaging 3.8%, for the Bond Variability Test (BVT) (Brissette, Mihajlovic, & Sanuri, 2014). Retained samples from SVTs can also be continued later in a study, to measure the true SAGDesign hardness for SAG and ball milling design, as measured by the completed SAGDesign test. In other words every SAGDesign test includes a SVT result and every SVT can be completed later to full SAGDesign test status for higher accuracy and design purpose.

Table 1 compares the total number of samples and projects involving the SAGDesign and the SAG/Bond Variability tests results. It is noted that mostly half of the SVT samples were coming from the same project having very soft ore (< 5 kWh/t). This explains why the SVT database shown in Figure 4 seems to be softer than the SAGDesign database. No database for BVTs has been prepared as there is currently insufficient data to present a meaningful summary.

Table 1 – Total Number of Samples for each test in the SAGDesign Suite, Current August 2015

Test	Number of Projects	Number of Samples
SAGDesign	179	1006
SVT	6	216
BVT	1	18

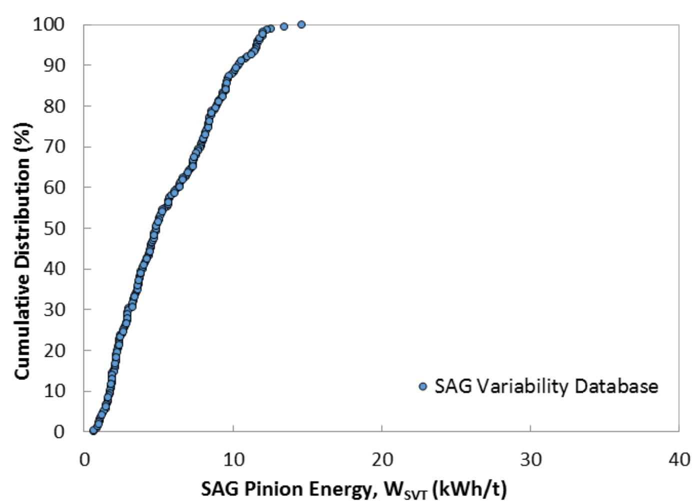

Figure 4 – SVT Database: SAG pinion Energy, W_{SVT} Vs Dist. %

Because the SVT and BVT commenced in 2013 and 2014 respectively, no plants using those tests have started yet. However, for that particular project with a large number of SVT tests and very soft ore, the results were used to increase the mill size and improve mine planning for years because the throughput fluctuations caused by ore hardness variability prevented achieving design tonnage during the payback period and future years as shown in Figure 5 and Table 2. The nominal design capacity of the plant was 120,000 tpd. Because the project was in the scoping stage, some years did not have any samples for metallurgical testing and the number of samples per year varied between 1 and 6. Some years did not meet design tonnage if operated as designed because during some years, the grinding circuit was either SAG mill or ball mill limited.

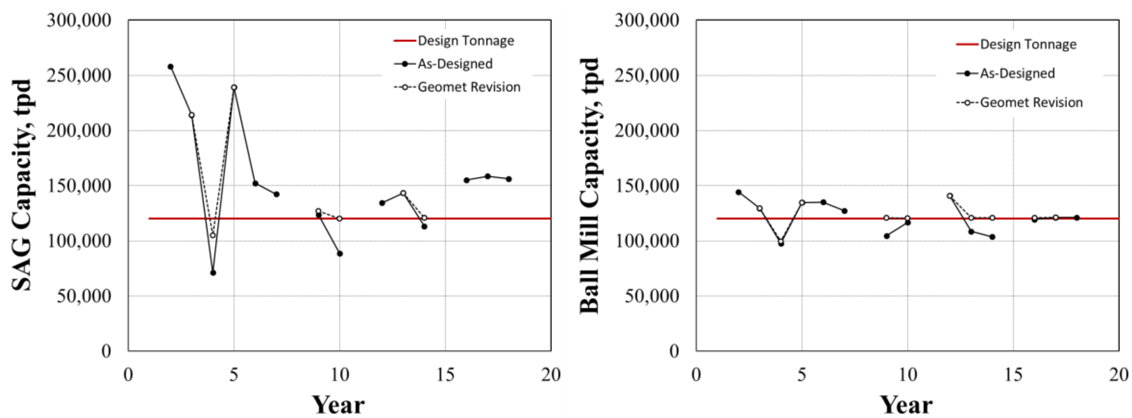

Figure 5: SAG and Ball Mill Capacity during Geometallurgical Scoping Study

For the SAG mill, the motor size was increased to operate with a high steel load (15%) at higher speed (77% Critical Speed) which was necessary for Year 10 only. Usually, S&A sizes a SAG mill for 10% ball load as standard design, with allowance to increase either the mill speed or the ball load but not both at the same time. This explains why only the installed power was increased. For the ball mill, the effective length and motor size were increased to increase its capacity and to accommodate a higher ball load (40%) respectively. Only one year was still problematic (Year 4) but only one sample was available with some competent ore ranking in the 95%th percentile of the ore hardness profile. It was decided to revise the mine plan rather to increase further the size of the equipment. It is also noted that only one sample was available for Year 10 with a hardness ranking at the 90%th percentile. The mine plan can also be revised to decrease the motor sizing of the SAG and reducing the capital cost.

Table 2 – Mill Sizing Recommendation with Geometallurgical Forecasting

	Number of Mills	SAGDesign Methodology	Geomet Forecasting
SAG Mill	2	Ø38' x 17.9' EGL 16.3 MW	Ø38' x 17.9' EGL 17.2 MW
Ball Mill	4	Ø24' x 37.7' EGL 12.4 MW	Ø25' x 39' EGL 14.9 MW

The advantages of the SVT and BVT in the context of SAGDesign testing are several:

1. Many more samples can be tested without increasing the overall project cost.

2. In a large suite of samples, the SAG hardness can be measured first to provide a preliminary value before deciding which samples should be used for design.

3. SVT is comparable to other methods while providing better accuracy.

4. Less total sample material is needed to conduct a complete SVT/SAGDesign program as both tests are conducted on the same sample.

5. The highly accurate SAGDesign test is used for design and its data fits in well for use with the SVT data for production forecasting and control if the tests are part of a suite of geometallurgical samples. (Starkey, Meadows, Thompson, & Senchenko, 2008).

MATCHING TEST ACCURACY WITH PROJECT STAGE

The ability to upgrade the quality of a mill design to match the project stage without significant additional sampling is one of the best achievements in the 10 year history of SAGDesign testing. This refers of course to the final stage of a project where usually the level of data available for the cost and revenue estimates is Feasibility Study quality, roughly ±15%. This should be upgraded to ±5% before the mills are purchased in order to ensure that these mills will perform as intended (Meadows, Scinto, & Starkey, 2011). This can be done through additional sampling and testing of ores when sample material is available to achieve a further degree of confidence through duplications and data volume. However if SVT data was used in prior work, the same samples can be used for the upgrade by recovering the samples from storage at the lab and completing the SAGDesign tests to take advantage of a higher degree of test accuracy.

If some other test methods are used, then between 5 and 10 new samples should be taken upon review of the existing data and tested using SAGDesign or a test of equivalent quality to accomplish the upgrade in design accuracy to a level suitable for mill purchase. A number of projects have been tested in this way. Examples are:

Kazakhmys , Kazakhstan

Detour Lake, Canada

Fedorova, Russia

Aurora Uranium, Canada

Minto, Canada

Bistrinskoye, Russia

NICO – Fortune Minerals, Canada (Starkey & Samuels, 2010)

In every case, even though as few as four samples were tested, the SAGDesign results were robust and the data submitted was of great value in deciding how and whether to proceed with the project. The comparison of SAGDesign testing with other methods showed that there was good agreement in some cases and in others that the SAGDesign measurements were valid even though there were some challenges with the other methods for various reasons not included here.

The importance of upgrading data at the final stage before purchase was recommended at SAG 2011 in the paper entitled "Seeking Consensus, etc." (Meadows, Scinto, & Starkey, 2011). Looking at the failed start-ups in Canada in the last four years, it is probable that this final check is not being done. The reason for this is not clear. Decisive action at the time the project is being considered for final engineering design can easily allow the required SAG testing results to be available in time for the mill purchase order, and the correct equipment layout considerations to be implemented. If the project team believes that saving money on the price of the SAG mill is in the client's interest, it can be said with complete confidence that this is not true (Starkey, Brissette, Larbi, & Meadows, 2013). Retrofitting costs of over CAN$50,000,000 have been recorded and revenue losses of even greater amounts during the first year are evident due to limited throughput. Data like this shows that the 43-101 reports being issued to the public for new projects should require a guideline for best practices in testing, mill design, and throughput calculation methodologies, so that all of the contained data matches. Future work will document this situation.

SUCCESSFULLY COMMISSIONED PROJECTS

The following SAG milling plants in Table 3 have been designed, or have had the final design checked using SAGDesign technology. In these eight cases the selected equipment performed well. No deficiency reports have been made.

Table 3 – List of Successful SAG Project Start-ups in Recent Years Using SAGDesign

PROJECT	ktpd	Date	SAG Dimension	SAG kW
Mecator, USA	45.3	Oct '08	Ø28' x 8' (2x)	4,500
Tenke Fungurume, DRC	7.6	Mar '09	Ø22' x 23.5'	5,500
Tabokoto, Mali	5.0	Q1 '12	Ø26' x 12.5'	4,000
Climax Moly, USA	27.6	May '12	Ø34' x 14.3'	13,500
Detour Lake, Canada	45.0	Jan '13	Ø36' x 20' (2x)	15,000
Alexandovskoye, Russia	2.2	Q2 '13	Ø22' x 10.2'	2,300
Belaya Gora, Russia	4.8	Q2 '13	Ø22' x 9.3'	2,150
Lake Shore Gold, Canada	3.3	July '13	Ø22' x 35'	3,700

Note: Tenke Fumgurume SAG mill dimension were changed and the power increased to that shown at the time of mill purchase in order to meet long term increasing ore hardness.

There are many other successful start-ups in recent years but these are not included because S&A does not have the design data and the subject of this paper is to discuss SAGDesign testing.

CONCLUSIONS AND RECOMMENDATIONS

If the grinding mill design has not been done using a test program which provides design hardness values with an accuracy of ± 5% as required for the EPCM stage, a final stage of testing needs to be implemented. This must be part of accepted best practice mill design standards. These samples must be chosen by a qualified engineer/geologist to represent the actual mine production, focusing on early mine life.

Every project designed or evaluated prior to construction with SAGDesign testing has produced design tonnage. Therefore, the use of SAGDesign testing and technology is concluded to be one way to achieve the project specified production performance goals.

To achieve similar confidence in a design, S&A strongly recommends making the ability to start a new SAG plant at design capacity the best practices goal for any new mining project. The improvement to financial performance in a new plant when this is possible is significant as evidenced by the cost of retrofitting and the low revenue, when initial production is less than design t/h.

The acceptance of ramp up schedules for starting a SAG plant can hide the lack of SAG capacity for months before the problem with ore hardness is discovered, and should therefore be avoided.

The development of SAGDesign testing and technology is essentially complete and has passed every test and challenge that has occurred in the past 10 years with flying colours. We look forward to sharing a similar positive summary of SAG Variability and Bond Variability Testing in the future.

The principal author wishes to thank those clients and our 10 business partners who over the past 10 years have trusted our work, paid for our technology and services, and supported our designs by purchasing the necessary laboratory equipment and licenses, and the recommended commercial grinding mills and motors for production plants and concentrators. It is to their credit that a successful way to design SAG mills has emerged as an open technology.

REFERENCES

Brissette, M., Mihajlovic, V., & Sanuri, S. (2014). Geometallurgy: New Accurate Testwork to Meet Required Accuracies of Mining Project Development. *International Mineral Processor's Conference.* Santiago, Chile.

Felsher, D. B. (2015). Overview of Lake Shore Gold's 2012 - 2013 Bell Creek Mill Expansion. *Canadian Mineral Processor's Conference.* Ottawa, Canada.

Meadows, D., Scinto, P., & Starkey, J. H. (2011). Seeking Consensus - How Many Samples and What Testwork is Required for a Low Risk SAG Circuit Design. *SAG Conference.* Vancouver, Canada.

Senchenko, A. Y., Kulikov, Y. V., & Starkey, J. H. (2014). New Project in Russia with Semiautogeneous Mill Selected According to the Results of SAGDesign Testing. *International Mineral Processor's Conference.* Santiago, Chile.

Senchenko, A. Y., Kulikov, Y. V., & Starkey, J. H. (2015). New Projects in Russia for Hard and Soft Ores with SAG Mills Selected From the Results of SAGDesign Testing. *SAG Conference.* Vancouver, Canada.

Starkey , J. H., & Larbi, K. (2012). SAGDesign - Using Open Technology for Mill Design and Performance Assessments. *Procemin.* Santiago, Chile.

Starkey, J. H. (2015). Achieving SAG Mill Design Production at Start-Up Using Best Practices - Fact or Fiction. *International Comminution and Classification Congress 2015.* San Luis Potosi, Mexico.

Starkey, J. H., & Samuels, M. (2010). Successful Deisgn of the NICO Grinding Circuit for Unusually Hard Ore. *Canadian Mineral Processor's Conference.* Ottawa, Canada.

Starkey, J. H., Brissette, M., Larbi, K., & Meadows, D. (2013). Design SAG mill production when you need it most: In day 1 and year 1. *Procemin.* Santiago, Chile.

Starkey, J. H., Meadows, D., Thompson, P., & Senchenko, A. (2008). SAGDesign Testing Review - Case Studies. *International Mineral Processor's Conference.* Beijing, China

COPYRIGHT FORM FOR CIM

Title of Paper: ____

____

____

Author(s): ____

____

Copyright Transfer
I/We hereby agree to transfer the copyright of my/our paper to the Canadian Institute of Mining, Metallurgy and Petroleum (CIM), when the paper is accepted for publication in the SAG 2015 Proceedings. The contents of this paper have not been copyrighted, published, or submitted for publication elsewhere.

Author(s)'s Signature(s)

Date ____

Name(s) (please print) ____

If this paper represents work made for hire:

Name and title of the person for
whom work was done (please print) ________________________________

____

Authorizing signature: ________________________________

- **IF YOU SUBSEQUENTLY SUBMIT YOUR PAPER TO ANOTHER PUBLICATION, PLEASE BE SURE TO INDICATE THAT THE PAPER WAS FIRST PUBLISHED IN THE SAG 2015 PROCEEDINGS, CITING LOCATION AND DATE.**
- **IF YOUR PAPER, OR SUBSTANTIAL PARTS OF IT, HAVE BEEN PUBLISHED ELSEWHERE AND ARE ALREADY UNDER COPYRIGHT TO ANOTHER ENTITY, THEN IT IS YOUR OBLIGATION TO ENSURE THAT CIM CAN HOLD JOINT COPYRIGHT WITH ALL OF THE ASSOCIATED RIGHTS AND PRIVILEGES.**