SPI® - A DECADE LATER

ABSTRACT

The MinnovEX SAG Power Index (SPI®) test is celebrating its 10th year of industry use as a primary source of ore data for grinding circuit design, optimisation, or production forecasting. While having enjoyed extensive use and commercial success world-wide there are a number of questions that are frequently encountered. Notable among these are:

- Why use a small scale SAG® mill as a data source for SAG and AG mills?
- How large a role does abrasion play in the SPI® mill?
- Can critical size build-up be predicted and does SPI® data suggest strategies for addressing it?

These and other questions will be answered. Technical and economic conditions that led to the development of the test and a few usage statistics will also be discussed.

WHY WAS THE SPI® TEST CREATED?

The short answer to this question is that most mineral deposits are metallurgically variable; this variability must be taken into account in grinding studies for design, optimisation, or production forecasting purposes; and until 1995 there was no reliable and economic means of capturing this variability in a study data set. This intrinsic variability is shown in Figure 1 and Figure 2 which are cumulative frequency distributions for SAG Power Index (the hardness of the ore from a SAG/AG milling perspective) and for Bond work index. Figure 3 is a hardness surface (SPI®) for a copper porphyry bench in a major South American mine.

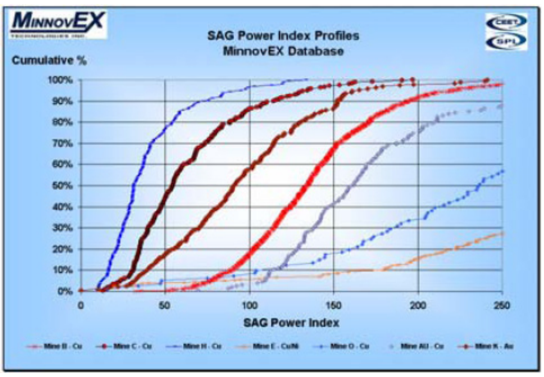

Figure 1 - SPI® distributions for several properties

GRINDABILITY TESTS OPTIONS PRIOR TO 1995

A number of tests were available a decade ago but they all required large diameter core, vast amounts of material, or both.

Most exploration is done using NQ core (47 mm) so the tests that required larger diameters (e.g. single particle breakage tests) compelled the feasibility team to source large core drilling equipment and embark on a special campaign to obtain samples specifically for metallurgical testing. The extra expense could not be shared with the resource definition budget (as this was being done with NQ core) and had to be borne solely by the metallurgical budget. Large diameter core is particularly expensive to drill so it is not surprising that it accounted for only a small fraction of the total meterage.

Grinding pilot plants required hundreds of tonnes of ore typically obtained from a shaft or adit sunk into the upper regions of the orebody. The high cost of this mini-mining activity inevitably meant that only one location was sampled, and this location was selected for accessibility reasons as well as for metallurgical ones.

Large sample requirements, special core drilling programs, and small metallurgical test budgets combined to force the design team to seek ways to supplement

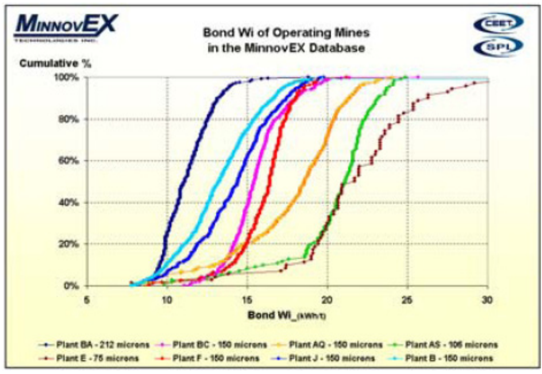

Figure 2 – Bond work index distributions

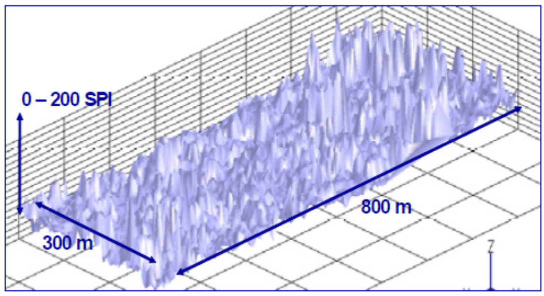

Figure 3 – Hardness surface of a bench

SGS

their small costly metallurgical data with relationships to other more abundant data sources. A logical choice was to leverage the existing geological data that came from the resource definition drill program. After all, geology describes the rock, at least from a mineral, genesis, and alteration perspective. This must have some relation to the structure and thus grindability of the rock, shouldn't it? And so because economics precluded a rigorous mapping of the deposit convenient assumptions were made about the relationship between geology and grindability – assumptions that have lasted for decades despite mounting evidence suggesting that the relationship is not as strong as we would like.

By the early 1990's John Starkey was convinced that a SAG version of the Bond ball mill work index test was needed if the industry was to improve upon current practice. John, an experienced pilot plant manager and feasibility engineer, experimented with a bench scale SAG test protocol. He brought his findings to the attention of MinnovEX Technologies Inc. in 1994 and the Starkey SAG test evolved procedurally into the MinnovEX SAG Power Index test. Immediately MinnovEX embarked on an extensive industrial calibration campaign. Today over 8,500 $SPI_®$ tests have been conducted and the test calibration is based on more than 300 detailed grinding circuit surveys for SAG and AG operations world-wide.

WHAT IS THE $SPI_®$ TEST?

Our quest for perfect data must be balanced against practical realities. The only way to approach perfection in our data set would be build a full scale grinding circuit and mill the entire orebody. Since this is clearly not an option every test will be a compromise in one form or another. John Starkey and MinnovEX decided to follow the Bond example and scale the grinding process down, balancing sample size and cost. To permit the metallurgical variability of the deposit to be clearly seen in the data set the $SPI_®$ test was designed to use existing exploration drill core. We recognised that this core represents the physical geological record of the resource so split NQ was targeted as the typical feed stock for the test and only two kilograms of sample was used. A rigorous closed circuit crushing procedure was developed to bring all samples to a standard feed size distribution. The test is done dry in a fixed speed laboratory scale SAG mill, with iterative grinding and screening sessions bringing the ore charge to a standard product size distribution. The time required to do this standard size reduction is the SAG Power Index for that ore sample. Since all of the test parameters are fixed a higher $SPI_®$ means that more grinding was needed to reduce the sample to the end point and thus more energy was used. The SAG Power Index is not linearly correlated with specific energy as the Bond work index is, but then again, the Bond work index is not raw data in the true sense of the word. The Bond test is conducted to simulate a 250% circulating load and once the test has come to equilibrium the raw data are:

Gbp (the average of the last three cycles of grams of minus closing screen material per revolution)
P_{80}
F_{80}

These are entered into a work index model of the form:

$$BW_i = \frac{49.1}{P_i^{0.23} \cdot Gbp^{0.82} \cdot \left(10/P_{80}^{1/2} - 10/F_{80}^{1/2}\right)}$$

The resulting BWi has the units of kWh/t and is meant to be used in a second equation known commonly as Bond's third theory of comminution:

$$kWh/t_{BM} = BW_i \cdot \left(10/P_{80}^{1/2} - 10/F_{80}^{1/2}\right)$$

So the BWi is an intermediate parameter that has been created to be linear with energy even though the raw data that is used to generate it is not. The $SPI_®$ on the other hand, is not treated to an intermediate calculation step. It is designed to be directly used with an integrated grinding circuit modelling system known as $CEET_®$[1]

FREQUENTLY ASKED QUESTIONS

WHY USE A GRINDING TEST AND NOT SINGLE PARTICLE BREAKAGE TESTS FOR YOUR DATA SOURCE?

The names alone suggest why. Grinding test sounds very much like the action of full scale SAG mills. Single particle breakage does not. The grinding environment in a SAG mill is highly complex. Massive amounts of computer power derived from parallel processing computer systems are needed just to model the larger size fractions of a SAG mill[2]. Computational fluid dynamics is then employed to model the finer fractions. All this effort can only describe charge motion and not breakage. Instead of attempting to simplify the grinding environment we have elected to reproduce it (within the constraints imposed by our decision to use split exploration core as feed stock).

Rock breakage can be classified within four broad categories – impact, single particle nipping, autogenous compression, and abrasion. All of these mechanisms are present in the $SPI_®$ mill. The ratio of each varies widely depending largely on the ore itself (friability and hardness) but also on the equipment geometry, speed of operation, rheology, ball size, charge SG, etc. All of the machine parameters are held constant within the $SPI_®$ test, leaving only the ore as the variable. Thus for one well defined grinding environment the net result of the highly complex milling process can be expressed as time to do a standard size reduction and it is reported as the SAG Power Index. Simulation based on extensive industrial calibration is then used to translate the index into kWh/t and ultimately into detailed SAG circuit performance (T80, t/h, pebble crusher circulating load, etc.) for specific SAG milling environments.

MinnovEX's approach can be

[1] $CEET_®$ is an acronym for Comminution Economic Evaluation Tool. It was developed by MinnovEX Technologies with technical and financial support of 13 major mining companies. It has been used for years to design world class grinding circuits and represents the new benchmark in design methodologies.
[2] The author is referring to DEM or discrete element method.

summarised as preserving the intrinsic complexity of the grinding process in the test, extracting ore-specific parameters, and then employing these parameters within energy-based process models to run design, optimisation, or forecasting simulations.

Single particle breakage tests (followed by population balance modelling) greatly simplify the breakage environment by separately testing rock samples in impact and abrasion devices to obtain size distributions (appearance functions) for high and low impact events. This is followed by the fitting of an empirical energy-appearance function relationship. An assumption is then made that the appearance functions measured in carefully controlled laboratory tests both scale up to untested sizes and remain the same in the crowded, chaotic milling environment. Plant surveys are then needed to obtain feed and mill discharge size distributions. These distributions combined with the energy-appearance function relationship obtained from the lab, are used to back-calculate a breakage rate curve. This breakage rate curve is at the end of a series of carefully controlled laboratory measurements, empirical relationships, and assumptions. There are multiple combinations of appearance functions and breakage rates that would describe any mill discharge stream and there is no way to independently verify the breakage rate curve. It is essentially a fitting function.

Consider some of the assumptions that are implicit in the population balance approach. First there are only two of the breakage mechanisms represented in the data collection exercise – impact and abrasion. Single particle nipping and autogenous compression, both found in the body of the charge as it turns over on itself, are missing. One can only conclude that the practitioners of the population balance approach have assumed that these two mechanisms are not significant contributors to the size reduction process within a SAG mill or are somehow co-represented within the two mechanisms that they do test. Another large assumption stems from the source of the impact data. The drop weight tester measures a very specific impact event. One that is characterised by a lump carefully placed on an anvil whereupon a flat piece of steel strikes the lump. The path of the hammer is precisely perpendicular to the rock. However, in practice the cataracting and cascading charge will yield countless glancing blows and side impacts. Can one assume that the appearance functions from these events are exactly the same as those derived from carefully controlled laboratory measurements where only one geometry is represented?

Another issue to consider is the growing acceptance that the collision history of a lump can have an effect on the specific energy that will cause failure. A lump that experiences a series of sub-failure impact events may break at a significantly lower specific energy than an identical one that has not been subjected to a similar beating. Single particle breakage tests do not account for this in any way. The SPI® test on the other hand, is a laboratory scale SAG mill and as such, the particles in the mill undergo much the same collision history that commercial scale lumps do.

The single particle breakage approach can be summed up as greatly simplifying the grinding process in the laboratory, extracting ore-specific parameters, and then simulating using these parameters in population balance-based models calibrated to industrial operating mills.

The SPI approach follows Bond's example and to the extent possible, preserves and uses the complexity of the grinding process within the SPI® test.

Table 1 Communition test comparison

Test	Single particle breakage (population balance)	SPI® test
Impact breakage	Y	Y
Abrasion breakage	Y	Y
Nipping	N	Y
Autogenous compression	N	Y
Accounts for collision history of particles	N	Y
Preserves complexity of the grinding process	N	Y
Similar environment to industrial mill	N	Y
Largest particle size represented	65 mm	19 mm

IS THE SPI® AN ABRASION TEST?

Charge motion and breakage are linked in a highly complex manner within a grinding mill. From a phenomenological perspective we can draw safe conclusions that low energy ball-particle interaction will likely result in an abrasion event while a high energy collision may produce a shattering of the particle on impact. Low and high energy in this context is in relation to the particle size and mass. Thus we will consider the magnitude of a breakage event in terms of the energy specific to the particle mass. Since the units of specific energy are kWh/t or J/kg, a small ball dropped from a shorter height can have the same specific energy of collision as is found in a commercial mill if the particle that it lands on is small enough.

By comparing the specific energy for the collision of a ball and a particle at the 80% passing size for the feed size distribution we will have a useful tool for gauging whether the breakage environment in a small scale mill is similar to that of a commercial mill. If the specific energy in the test mill is much lower we can reasonably speculate that there is much less impact breakage that would be found in a full scale mill and that abrasion is the dominant breakage mechanism. Is this the case for the SPI® test?

Two approaches to answering this question are presented. The first involves a rigorous calculation of the ballistic trajectory of a ball, its impact velocity, the kinetic energy at the impact site and the resulting specific energy of collision with a particle at the 80^{th} percentile of the feed size distribution. This calculation has been done for a commercial mill (32' diameter), a pilot plant mill (6' diameter), and the SPI® mill (12" diameter).

The second method is much simpler. It looks at the drop height of a ball and calculates its potential energy. The specific energy of collision is not calculated based on ballistic kinetic energy as in the first method. Rather it is derived by taking the ratio of the potential energy to the mass of a particle at the 80th percentile of size. Both methods give a specific energy value in J/kg.

Ballistic method

The equations used to calculate the ball trajectory are given in Table 2 and the terms are listed in Table 3.

Table 2 Ballistic equations

ballistic equations	
horizontal	vertical
vx = v0x	ay = -g
x = v0xt	vy = v0y -gt
	y = v0yt - 0.5gt^2

Table 3 term explanations

v_x	Velocity in the x dimension
v_{0x}	Initial x dimension velocity (at ball release)
x	Position in the x dimension
t	Time from ball release
a_y	Acceleration in the y (vertical) dimension
v_y	Velocity in the y dimension
v_{0y}	Initial y dimension velocity (at ball release)
g	Acceleration due to gravity

Table 4 lists the details of the commercial mill, in this case a 32 foot diameter SAG mill. The interior diameter accounts for the mill liners.

Equations for the mill shell (seen as the circle in Figure 4) and for the ball trajectory (parabolic curve) are solved simultaneously to obtain the coordinates of the impact point and velocity (see the yellow line in Figure 5).[3]

The impact velocity obtained from Figure 5 is then used to calculate the kinetic

Table 4 Mill details (commercial mill)

Commercial mill				
Mill diameter (interior)	372	inches	9.449	m
Diameter minus particle width			9.149	
Release height	318		8.07	m
Release angle	48			
Rotation speed	8	rpm		
One revolution in	7.5	s		
Angular change	48	deg/s	30	m
Circumference (inside)			4.0	m/s
Tangential velocity				
v0x			2.8	m/s
v0y			2.8	m/s
vx			2.8	m/s

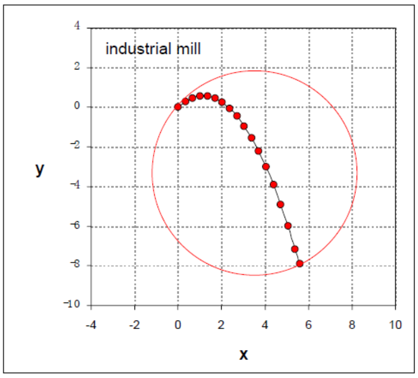

Figure 4 Ball trajectory (commercial mill)

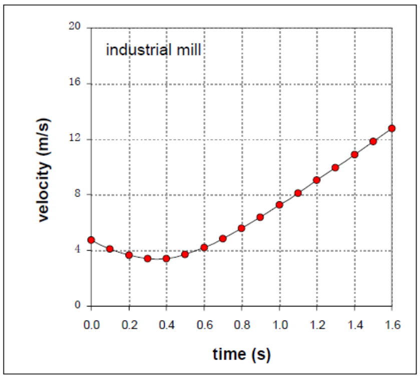

Figure 5 Impact velocity profile (commercial mill)

energy of collision which for a 5" steel ball in a 32' diameter mill would be 685 joules. Assuming a feed size distribution with a P_{80} of 150 mm[4] the specific energy of impact would be 144 J/kg for the P_{80} size. Details are given in Table 6.

Similar calculations were done for the SPI® mill and the pilot plant mill.

Table 5 Impact energy details (commercial mill)

Ball data						
Impact velocity	12.8	m/s				
Ball diamter	5	inch	127	mm		
Ball volume			1072531	mm^3	1072.53	cc
Ball S.G.	7.8	g/cc				
Ball mass	8366	g				
E_K	685	J				

Rock data				
Top size diameter	150	mm		
Spherical volume	1767146	mm^3	1767.15	cc
Rock S.G.	2.7	g/cc		
Rock mass	4771	g		
$E_{Specific}$	**144**	**J/kg**		
	39.9	kWh/t		

Potential energy method

Table 6 lists the details used in calculating the potential energy of a ball elevated to the release height in each of the mills. The potential energy formula is:

PE = mgh

Both methods for calculating collision specific energy are summarised in Table

[3] The equation for the inner mill shell has been derived such that the release point of the ball is at the origin (0,0).
[4] This was targeted as the standard feed size distribution during the development of the SPI® test.

Table 6 Mill details for potential energy calculation

	SPI mill		Commercial SAG		Pilot plant	
release height	0.26	m	7.93	m	1.56	m
ball mass	0.13	kg	8.4	kg	8.4	kg
PE =	0.33124	J	653	J	128	J
Rock mass	0.00276	kg	4.77	kg	4.77	kg
SE =	120	J/kg	137	J/kg	27	J/kg

7. Some very interesting observations can be made from these data. First, the specific energy of collision for at least one narrowly defined event (a clean strike from a ball onto a particle at the 80th percentile of feed size) is very similar for both the SPI$_®$ mill and a 32' diameter SAG mill. Interestingly, the pilot plant has a far lower impact energy value. Does this mean that the pilot plant is a predominately abrasion device? No, this analysis is focused on a single narrowly defined event. However, given the similarities between the SPI$_®$ mill and a commercial SAG mill as seen in Table 7, we can safely say that impact breakage is well represented in the SPI$_®$ mill.

The following analysis seeks to identify the size classes where each of the main breakage mechanisms dominates. The feed to the SPI$_®$ test is the result of a rigorous closed circuit crushing procedure that yields a distribution of particle sizes with an F_{80} of 12.5 mm. For this analysis very tight rock charge particle size ranges were created and an SPI$_®$ test was conducted for each. For example, 2 kg of minus 16,000 plus 12,500 micron lumps were ground in an SPI$_®$ mill with screening done at regular intervals. Broken material was not returned to the mill after each cycle. The data was analysed to determine the rate of parent mass loss and the particle size distribution of the progeny. This was done for a complete range of size class bins.

The screen analysis data has been converted to vector probabilities and is reported in Table 8 and Table 9. For example, for the minus 19,000 plus 16,000 fraction there is a 91.2% probability that mass will remain in that same (parent) fraction. Similarly, there is a 7.6% probability of mass reporting to the next fraction (in this case the minus 16,000 plus 12,500 fraction), a 0.6% probability of mass reporting to any of the other fractions except sub-sieve (106 microns), and a 0.5% probability of mass making it to the sun-sieve.[5]

Table 7 Summary of collision specific energy

Test	$E_{specific}$ Ballistic method	$E_{specific}$ Potential energy method	% of commercial mill energy (Ballistic method)
Commercial mill	144	137	100%
SPI$_®$ mill	125	120	875
Pilot plant mill	26	27	18%

Table 8 – Probability table for one cycle

Probabilities normalized to one cycle				
Size	**SAME**	**NEXT**	**OTHER**	**SUBSIEVE**
16000	91.20%	7.63%	0.64%	0.53%
12500	92.65%	4.58%	1.97%	0.80%
9500	80.97%	10.95%	6.67%	1.45%
6700	67.75%	15.87%	14.99%	1.51%
3350	70.14%	8.61%	19.61%	1.63%
1700	73.97%	8.51%	15.61%	1.90%
850	81.83%	7.78%	8.26%	2.12%
425	82.71%	7.06%	6.57%	3.66%
212	83.49%	7.28%	2.86%	6.36%

In Figure 6 we have plotted the percent weight loss for each of the size classes after one cycle in the SPI$_®$ mill and an interesting trend has emerged. The larger classes are characterised by low weight loss, the middle ones a much larger mass loss, and the finer classes somewhere in between. Before we draw any conclusions let's examine the product size distribution for each class.

Table 9 takes a closer look at the distribution of particle sizes that exited the parent class. Of the mass that would break to the fractions below the parent, their distribution has been reported as percentages of the total mass that exited the parent class and not as a percentage of the parent mass. So once again for the

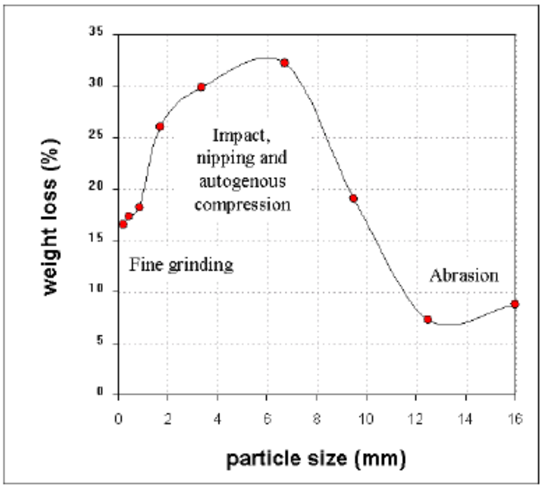

Figure 6 Weight loss by size class in the SPI mill tests with narrow feed size classes. Original ore had an SPI of 62 minutes.

[5] Probabilities were used in this study for their additive properties that have found utility in subsequent data manipulations that will not be reported on in this paper.

minus 19,000 plus 16,000 fraction 87% of the mass that left would descend only one size class (to the minus 16,000 plus 12,500 class). In other words, most of the broken mass can be found in the adjacent size class indicating that these particles were probably near mesh and with a slight bit of grinding they were able to slip through the screen. Little mass went to any of the other size classes but almost half of what did, went to the sub-sieve fraction (very small). All of this points clearly to abrasion being the dominant process for the minus 19,000 plus 16,000 class.

For the intermediate size classes there is a much higher mass loss out of the parent class and what did break out reported more heavily to the middle (other) classes and not nearly as much to the adjacent (next) class. This suggests coarse breakage in line with impact, single particle nipping, or autogenous compression.

HOW IS IT USED?

The SAG Power Index Test is the source of rock-specific data for energy-based grinding models embedded within the CEET® comminution simulation system. While the index itself provides semi-quantitative information about the performance of a grinding circuit processing the tested ore, it is designed to be used within CEET® for design, optimisation, or production forecasting studies. A separate paper elaborating on CEET® has been submitted at this conference so the standard simulation details will not be addressed here.

Table 9 – Distribution of breakage products[6]

Distribution of the daughter possibilities					
Size	**Sum of daughter probabilities**	**NEXT**	**OTHER**	**SUBSIEVE**	**CHECK SUM**
16000	8.80	86.7%	7.3%	6.0%	100.0%
12500	7.35	62.2%	26.9%	10.9%	100.0%
9500	19.03	57.5%	35.1%	7.4%	100.0%
6700	32.38	49.0%	46.3%	4.7%	100.0%
3350	29.86	48.9%	65.7%	5.5%	100.0%
1700	26.03	32.7%	60.0%	7.3%	100.0%
850	18.17	42.8%	45.5%	11.7%	100.0%
425	17.29	40.8%	38.0%	21.2%	100.0%
212	16.51	44.1%	17.3%	38.5%	100.0%

Parent size	Weight loss (one cycle)	Distribution of daughter particles	Analysis	Dominant breakage mechanism
Large (12,500 to 16,000)	Small	Most in adjacent size class with much of the remaining going to sub-sieve	Low weigh loss, near mesh particles sliding to the adjacent class, and sub-sieve material making up much of the remainder all point to abrasion as the dominant mechanism	Abrasion
Middle (425 to 9,500)	Medium to high	Substantial amount reporting the adjacent class but large amounts breaking to the middle (other) classes. Little mass breaks to sub-sieve.	High weight loss with coarse breakage products suggest both impact and in-charge particle nipping as the main breakage vehicles	Impact and nipping
Small (212)	Medium	The 212 class had most of the broken mass going to the next and sub-sieve classes much like the large parent classes.	The breakage in this fine regime may return to abrasion as there is a very high particle surface area but not many breakage sites. Finer media would likely shift the progeny to coarser classes.	Abrasion

[6] The other fraction represents all of the size classes below the next class and larger than sub-sieve (106 micron). This range is different for each parent class. We have calculated the midpoint of the other class for each parent class. It is the second bar in the following figures.

WHERE IS THE SPI® TEST BEING USED?

To date over 8,500 SPI® tests have been conducted and the industrial calibration is now based on extensive data collected from 300 benchmark surveys conducted on SAG and AG circuits world-wide. Many design projects have been done over the years including several of the largest grinding circuits now in operation8. The SPI® test is also central to several rigorous production forecasting programs at world-class copper and iron ore operations. A complete reference list is available from MinnovEX.

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