GLOBAL MINING GUIDELINES GROUP

GMG

DETERMINING THE BOND EFFICIENCY OF INDUSTRIAL GRINDING CIRCUITS

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Global Mining Guidelines Group (GMG)

ABOUT GMG

The Global Mining Guidelines Group (GMG) is a network of representatives from mining companies, original equipment manufacturers (OEMs), original technology manufacturers (OTMs), research organizations and academics, consultants, regulators, and industry associations around the world who collaborate to tackle challenges facing our industry. GMG aims to accelerate the improvement of mining performance, safety, and sustainability by enabling the mining industry to collaborate and share expertise and lessons learned that result in the creation of guidelines, such as this one, that address common industry challenges.

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GMG was formed out of the Surface Mining Association for Research and Technology (SMART) group as part of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) and with the support of other Global Mineral Professionals Alliance (GMPA) members.

GMG is an independent, industry-led organization.

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Once the guideline is reviewed and accepted by the project group steering committee, working group members peer review and GMG members within the working group vote to approve draft documents prior to their approval by the GMG Executive Council.

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- **Landscapes:** Reviews of ongoing related work by other organizations on a key topic. These aim to provide the industry with an idea of what exists and prevent duplication of effort.
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CREDITS

The following organizations and individuals were involved in the preparation of these guidelines at various stages including content definition, content generation, and review. Please note that the guidelines do not necessarily represent the views of the organizations listed below.

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Determining the Bond Efficiency of Industrial Grinding Circuits

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EXECUTIVE SUMMARY

The Work Index (Wi) was defined by Bond as the comminution circuit equipment's needed specific energy input (W, in kWh/t) to reduce ore from a very large size (80% passing, or an F80 of infinity) to a circuit product size of 80% passing (a P80 of) 100 µm. Bond's Work Index Equation then relates all size reduction processes back to this value based on the observation that specific energy is related to the inverse of the square root of the circuit feed and product sizing, as follows.

$$Wi = \frac{W}{\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)}$$

In order to specify the design energy (W) input delivery requirements for new plants, laboratory tests were developed and scaled to a large database of plant (crushing, rod, and ball milling) equipment specific energy usages. The outcome of these tests provides Standard Circuit Bond Work Index (Wi_{STD}) values of the ore for crushing (Wi_C), rod milling (Wi_{RM}) and ball milling (Wi_{BM}). The W values calculated through this process can be totaled for the subsequent stages of crushing, rod milling, and ball milling. The Standard (design) Bond Work Index (Wi_{STD}) for the combined stages of this standard circuit may then be back calculated.

A plant circuit's Actual Operating Bond Work Index (Wi_{oACT}) is calculated from the respective plant data.

$$Wi_{oACT} = \frac{W}{\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)}$$

Comparison of the ratio between the test (or design) value of the Work Index with actual plant operating work index thus provides a measure of that circuit's energy usage efficiency relative to that specified for crushing, rod milling, and ball milling using the Bond test scale-up method.

$$\text{Wi Efficiency Ratio} = \frac{Wi_{STD}}{Wi_{oACT}}$$

The actual plant circuit can deploy any type of size reduction equipment. Thus, this tool can be used by operators and designers to benchmark the energy efficiency of any size reduction circuit, over the applicable size reduction range, that exists in the industry. Examples of calculation of Wi_{oACT} and Wi Efficiency Ratio for different industrial circuits are provided.

Bond Work Index laboratory testing equipment and procedures have been generally described by the developer, Allis-Chalmers Manufacturing Company. However, lack of precise details has resulted in significant variability in test results from the many laboratories (both commercial testing facilities and those at operating mine sites) throughout the world which conduct these tests. This document is intended to provide guidelines to standardize Bond test equipment and procedures and thus to minimize the testing experimental error. This will then minimize plant Bond Efficiency measurement error and maximize the usefulness of this efficiency value for performance benchmarking and process improvement.

ABBREVIATIONS

α	Angle to which the two hammers are raised from the vertical (degrees)
C	Energy per unit thickness to break a particle (J/mm)
C_{mean}	Mean energy per unit thickness to break the particles (J/mm)
d	Particle thickness between the points that it is contacted by the two hammers (mm)
F80	80% passing size of the circuit feed (µm)
gpr	Grams (new minus closing screen aperture) per mill revolution
IPP	Mass of Ideal Potential Product from a test cycle (g)
n	Number of fragments of a broken particle
P	Machine power at the pinion (for details, see Doll, 2021)
P100	100% passing size or closing screen aperture (µm)
P80	80% passing size of the circuit product (µm)
sg	Particle specific gravity (unitless)
SAG	Semi-Autogenous Grinding
T	Circuit tonnage (metric t/h)
t	Metric tonne
W	Specific energy (work) input (kWh/t)
Wi	Bond Work Index (kWh/t)
Wi_{BM}	Bond Ball Mill Test Work Index (kWh/t)
Wi_c	Bond Impact Crushing Test Work Index (kWh/t)
Wi_{oACT}	Actual Operating Bond Work Index determined from measurements on the circuit (kWh/t)
Wi_{total}	Total circuit specific energy (kWh/t)
Wi_{RM}	Bond Rod Mill Test Work Index (kWh/t)
Wi_{STD}	Standard Circuit Bond Work Index (expected or designed) used for circuit design. Specific energy requirement at the drive pinions.

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1. INTRODUCTION AND BACKGROUND

The Bond method in this guideline allows for quantification and comparison of the relative energy efficiency of most industrial comminution circuits. It is an important tool for evaluating the key cost components of common grinding circuits and their unit operations.

The objective of this guideline is to provide a benchmark metric for the specific energy requirements of an industrial grinding circuit, in comparison with a standard circuit designed with a set of standardized laboratory tests. The Bond Work Index (Wi) is the specific energy for a standard amount of size reduction: from a large F80 (80% passing circuit feed) to a P80 of 100 µm. The actual operating bond work index (Wi_{oACT}) is calculated from the comminution circuit, and the standard work index (Wi_{STD}) is determined by combining the results from three laboratory tests that measure the resistance to breakage over specific size ranges: coarse (Bond impact crushing), medium (Bond rod mill) and fine (Bond ball mill).

For early analyses of plant grinding efficiency issues, see Bond (1957, 1960).

2. SCOPE AND LIMITATIONS

This Bond Efficiency determination applies to most brittle materials in their naturally occurring (non-truncated) size distributions that are treated in size reduction circuits down to an 80% passing size of the circuit product (P80) of approximately 70 µm.

Bond calculations assume the natural, typically observed crushing, rod milling, and closed-circuit ball milling circuit product size distributions, which can be well represented by one (80%) cumulative passing size. Circuits with product size distributions that differ from this need special consideration in this context.

The method is subject to the following known limitations:

- Materials that generate unusually shaped particles (e.g., mica) should be regarded with caution, as they interfere with mechanical screening.
- The method of performing particle packing in the Bond ball mill work index test (5.3.3) has not been defined and is known to be a potential source of variability in laboratory testing.
- Specific instructions for the composition of sieve series, screen shaking, and interpolating the 80% passing size are left to the individual laboratories and are another potential source of variability.
- The closing screen used in the Bond ball mill tests should be chosen to achieve a similar product size to that achieved by the operating circuit.
- The Bond Efficiency, as calculated by this guideline, changes over time and should not be considered constant.
- This Bond Efficiency determination should not be applied to circuits with a P80 of finer than approximately 70 µm without making qualifications.

3. OTHER USEFUL DOCUMENTS

The Methods to survey and sample grinding circuits for determining energy efficiency guideline (GMG, 2016) provides guidance on how to collect information related to the operation of the circuit (F80, P80, power and mill feed rate).

4. DETERMINING THE BOND EFFICIENCY OF A GRINDING CIRCUIT

This section describes the method in the plant and laboratory and the calculations for determining the Bond Efficiency of a grinding circuit. It also provides examples to demonstrate this method.

4.1 Method

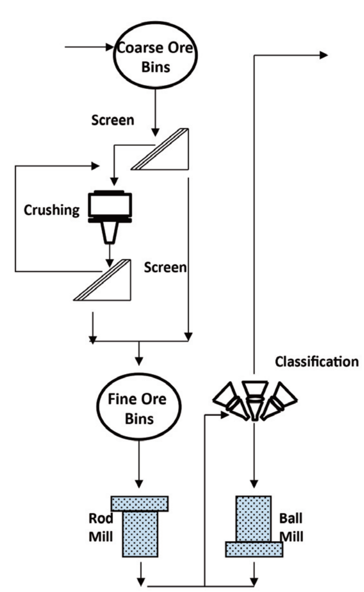
In the plant:

1	Define the circuit for which the Bond Efficiency is to be determined.
2	Procure samples of the circuit feed and product.
3	Obtain the power draw of the size reduction equipment at the drive pinion(s).
4	Obtain the circuit throughput rate (dry tonnage).

In the laboratory:

1	Conduct screen analyses of the circuit feed and product samples.
2	Conduct Wi test(s) on the circuit feed (see Section 5). Use a 1,190 µm screen to close the rod mill Wi test for these purposes. Choose a closing screen for the ball mill test that is one (standard square root of 2 series) mesh size coarser than the plant ball mill circuit P80. If choosing between two standard mesh sizes, choose the finer one. Rowland, C. A., Jr., (1986) notes from a trip to the Allis Chalmers laboratory that if you use 150 µm screen which is 100 mesh, you end up with something slightly coarser than the next screen down but depending on the material it can be just finer.

Calculations:

1	Calculate the Actual Operating Bond Work Index of the grinding circuit.	
	• Estimate the F80 and P80.	
	• Calculate the specific work or energy input from the size reduction equipment power (relative to the pinon for tumbling mills; see Doll, 2021) and circuit tonnage (equation 1). Auxiliary equipment power is excluded.	$$W = \frac{P}{T} \quad (1)$$ Where W is the specific work input (kWh/t), P is the equipment power (kW), and T is the circuit tonnage (metric t/h).
	• Calculate the Actual Operating Bond Work Index (equation 2):	$$Wi_{oACT} = \frac{W}{\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \quad (2)$$ Where Wi_{oACT} is the Actual Operating Bond Work Index (kWh/t), W is the specific energy input (kWh/t), P80 is the 80% passing size of product (µm), and F80 is the 80% passing size of circuit feed (µm).
2	Calculate the Standard Circuit Bond Work Index (Wi_{STD}) for the material being processed (equation 3):	$$Wi_{STD} = \frac{W_{total}}{\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \quad (3)$$ $W_{total} = W_1$ (crushing) + W_2 (rod milling) + W_3 (ball milling)
	The Bond Standard Circuit is the "conventional" crushing-rod-ball milling circuit that was popular circa 1950 to 1980, designed so that no correction factors apply to the Wi_{STD} (Figure 1). It is also the "design" Wi for this circuit based on the laboratory Wi test results. To avoid introducing design inefficiency factors into the reference Bond Standard Circuit, assume 2.44 m diameter overflow mills, and use a rod mill F80 of 16,000 µm and a rod mill P80 of 1,000 µm. Note that—in order for no correction factor for ball mill product fineness to apply—the ball mill circuit P80 should be no less than approximately 70 µm (Bond, 1962).	 Figure 1. The Bond Standard Circuit

3	Calculate the circuit Wi Efficiency Ratio (equation 4): $$\text{Wi Efficiency Ratio} = \frac{Wi_{STD}}{Wi_{oACT}} \quad (4)$$ Where Wi_{STD} is the Standard Circuit Bond Work Index (kWh/t) and Wi_{oACT} is the Actual Operating Bond Work Index (kWh/t).
	If the Wi Efficiency Ratio is 1.0 or 100%, the circuit is performing with the same efficiency as the Bond Standard Circuit (and the ore Wi = circuit operating Wi), in accordance with the correlation that Bond (1962) established between plant operating data and test data from his laboratory test equipment. That is, the circuit is using the same energy per tonne as the design energy predicted by the Bond design/scale-up method for the standard circuit, with no correction factors. If the Wi Efficiency Ratio is greater than 1.0 or 100%, the circuit is performing at an energy efficiency that exceeds the Bond Standard Circuit. If the Wi Efficiency Ratio is less than 1.0 or 100%, the circuit is performing at an energy efficiency that is lower than the Bond Standard Circuit.
	Note that a similar circuit efficiency parameter was published by C. A. Rowland, Jr. (please see references by Rowland, 1976 and 1998). This "Bond Standard Circuit Energy Factor" (equation 5) is equal to the inverse of the Wi Efficiency Ratio; it can be used by multiplying against the laboratory-derived Wi_{STD} to give the actual operating work index of a circuit, Wi_{oACT}. $$\text{Bond Standard Circuit Energy Factor} = \frac{Wi_{oACT}}{Wi_{STD}} \quad (5)$$

4.2 Demonstration/Example Calculations

4.2.1 Generic Circuit Calculation

Table 1. Values Used for Generic Circuit Calculations	
Parameter	**Value**
Power draw of mill(s) at pinion(s) (kW)	3,150
Circuit dry tonnage (metric t/h)	450
Circuit P80 (µm)	212
Circuit F80 (µm)	2,500
Test ball mill Wi of circuit feed ore (kWh/t)	16.1
Test rod mill Wi of circuit feed ore (kWh/t)	16.1

$$W = \frac{3{,}150}{450} = 7.0 \text{ kWh/t}$$

$$Wi_{oACT} = \frac{7}{\left(\frac{10}{\sqrt{212}} - \frac{10}{\sqrt{2{,}500}}\right)} = 14.4 \text{ kWh/t}$$

$$W_2 = 16.1 \times \left(\frac{10}{\sqrt{1{,}000}} - \frac{10}{\sqrt{2{,}500}}\right) = 1.87 \text{ kWh/t}$$

$$W_3 = 16.1 \times \left(\frac{10}{\sqrt{212}} - \frac{10}{\sqrt{1{,}000}}\right) = 5.97 \text{ kWh/t}$$

$$W_{total} = 1.87 + 5.97 = 7.84 \text{ kWh/t}$$

$$W_{STD} = \frac{7.84}{\left(\frac{10}{\sqrt{212}} - \frac{10}{\sqrt{2,500}}\right)} = 16.1 \text{ kWh/t}$$

$$\text{Wi Efficiency Ratio} = \frac{16.1}{14.4} = 1.12 \text{ or } 112\%$$

$$\text{Bond Standard Circuit Energy Factor} = \frac{14.4}{16.1} = 0.89 \text{ or } 89\%$$

This circuit is performing approximately 12% better than predicted by Bond, based on the average performance of the plant circuits that Bond correlated with his laboratory testing. This circuit is consuming 89% of the Bond specified (design) circuit energy.

4.2.2 Common Plant Grinding Circuit Calculations

Table 2. Values used for rod-ball mill circuit calculations

Parameter	Value
W (kWh/t)	8.56
Circuit P80 (µm)	155
Circuit F80 (µm)	19,300
Test Wi of crushing (kWh/t)	9.8
Test Wi of rod mill (kWh/t)	9.5
Test Wi of ball mill (kWh/t)	9.8

1. **Rod-Ball Mill Circuit** (Single-Stage Ball Mill, Multi-Stage Ball Mill, or High Pressure Grinding Roll-Ball Mill)

$$Wi_{oACT} = \frac{8.56}{\left(\frac{10}{\sqrt{155}} - \frac{10}{\sqrt{19,300}}\right)} = 11.7 \text{ kWh/t}$$

- Bond Standard Circuit:

$$W_1 = 9.8 \times \left(\frac{10}{\sqrt{16,000}} - \frac{10}{\sqrt{19,300}}\right) = 0.07 \text{ kWh/t}$$

$$W_2 = 9.5 \times \left(\frac{10}{\sqrt{1,000}} - \frac{10}{\sqrt{16,000}}\right) = 2.25 \text{ kWh/t}$$

$$W_3 = 9.8 \times \left(\frac{10}{\sqrt{155}} - \frac{10}{\sqrt{1,000}}\right) = 4.77 \text{ kWh/t}$$

$$W_{total} = W_1 \text{ (crushing)} + W_2 \text{ (rod milling)} + W_2 \text{ (ball milling)}$$

$$W_{total} = 0.07 + 2.25 + 4.77 = 7.09 \text{ kWh/t}$$

$$W_{STD} = \frac{7.09}{\left(\frac{10}{\sqrt{155}} - \frac{10}{\sqrt{19,300}}\right)} = 9.70 \text{ kWh/t}$$

$$\text{Wi Efficiency Ratio} = \frac{9.70}{11.7} = 0.83 \text{ or } 83\%$$

$$\text{Bond Standard Circuit Energy Factor} = \frac{11.7}{9.70} = 1.21 \text{ or } 121\%$$

2. **Semi-Autogenous Grinding (SAG)-Ball Mill Circuit**

Table 3. Values Used for SAG-Ball Mill Circuit Calculations

Parameter	Value
W (kWh/t)	14.6
Circuit P80 (µm)	125
Circuit F80 (µm)	165,000
Rod mill F80 (µm)	16,000
Test Wi crushing (kWh/t)	16.0
Test Wi of rod mill (kWh/t)	14.5
Test Wi of ball mill (kWh/t)	13.8

$$Wi_{oACT} = \frac{14.6}{\left(\frac{10}{\sqrt{125}} - \frac{10}{\sqrt{165{,}000}}\right)} = 16.8 \text{ kWh/t}$$

- Bond Standard Circuit:

$$W_1 = 16.0 \times \left(\frac{10}{\sqrt{16{,}000}} - \frac{10}{\sqrt{165{,}000}}\right) = 0.9 \text{ kWh/t}$$

$$W_2 = 14.5 \times \left(\frac{10}{\sqrt{1{,}000}} - \frac{10}{\sqrt{16{,}000}}\right) = 3.4 \text{ kWh/t}$$

$$W_3 = 13.8 \times \left(\frac{10}{\sqrt{125}} - \frac{10}{\sqrt{1{,}000}}\right) = 8.0 \text{ kWh/t}$$

$$W_{total} = 0.9 + 3.4 + 8.0 = 12.3 \text{ kWh/t}$$

$$Wi_{STD} = \frac{12.3}{\left(\frac{10}{\sqrt{125}} - \frac{10}{\sqrt{165{,}000}}\right)} = 14.1 \text{ kWh/t}$$

$$\text{Wi Efficiency Ratio} = \frac{14.1}{16.8} = 0.84 \text{ or } 84\%$$

$$\text{Bond Standard Circuit Energy Factor} = \frac{16.8}{14.1} = 1.19 \text{ or } 119\%$$

Note: 14.1 kWh/t is also the combined specific energy consumptions of the standard crushing, rod mill, and ball mill circuit (see Figure 1). The Wi Efficiency Ratio can also be calculated using the ratio of this specific energy consumption and the measured specific energy consumption of the circuit.

$$\frac{W_{total}}{W} \text{ of this SAG-ball mill circuit} = \frac{12.3}{14.6} = 0.84$$

5. WI TEST EQUIPMENT AND PROCEDURES

The following procedures were obtained from a report on a visit by R. E. McIvor in 1986 to the Allis-Chalmers manufacturing facilities in Milwaukee, WI, and laboratory facilities in Oak Creek, WI; the listed references; and discussions with the current inheritors of the original equipment and procedure and the staff at the testing laboratories of Metso in York and Danville, PA and Milwaukee, WI. They were further vetted with the members of the Bond Efficiency Subcommittee of the GMG Industrial Comminution Efficiency Working Group. Numerous other references describe or mention this test, but it is believed those listed in this guideline capture both its essence and sufficient details.

The aim of this guideline is to present the historic accuracy of the test as described in the references while also meeting the functional intentions of the developers. It is recognized that deviations from the equipment and procedures may be acceptable as long as the functional requirement of the test is achieved (i.e., it is able to reproduce the Wi value for the material being tested). Ultimately, calibration against accepted "standard" test equipment and procedures using reference samples will verify the acceptability of any deviations from this guideline.

It is also recognized that different laboratories will apply substantively greater detail in the sub-procedures for this test (e.g., packing density determination, screening load and times, use (or not) of calibrated screens, and determination of F80 and P80). This will greatly increase the reproducibility and comparability of test results from the same laboratory. Calibration against a "reference" laboratory will facilitate accurate comparisons of test Wi values among laboratories.

Discussion of test result variability (due to the nature of the ore, nature of specimens tested, and test equipment and procedures) is for future work.

5.1 Bond Crushing Wi Test for Bond Efficiency Determinations

The Bond Impact Crushing Work Index test provides the coarse size work index for the Wi_{STD} calculation, specifically the work index of sizes coarser than 16,000 µm. The work index result in this guideline is given in metric units, but readers should be aware that both short-ton and long-ton versions of this measurement appear in other literature.

5.1.1 Apparatus

Two hammers weighing 13.6 kg each are pendulum-mounted, such that when released, they track back on the same line on which they were raised and impact simultaneously on opposite sides of each rock specimen. The hammers are 51 mm × 51 mm × 25.4 mm deep. They swing on a 0.413 m radius arc. At rest, the two hammers are separated by a 51 mm gap—the thickness of the two hammer faces. When the hammers are released after being equally raised to angle "α" from the vertical, the impact energy is calculated (see Section 5.1.4).

Ideally, the spacing between the two hammer axes should be adjustable to allow for suitable (horizontal) impacts of the hammer faces on particles of different widths.

5.1.2 Sample

The entire sample is crushed so that all particles pass through a 76 mm square opening. Those particles subsequently retained on a 51 mm square opening are used. Note, for other purposes (e.g., crusher selection), Metso now specifies feed particles differently: They should be naturally occurring (crushed) pieces of broken rock taken from a more broadly sized sample source and have two near parallel faces that are between 51 and 76 mm in thickness. If this is the case, the Impact Crushing Wi nevertheless can be used in Bond Efficiency calculations. A minimum of 10 (preferably 20) pieces are tested.

5.1.3 Procedure

1	Weigh the specimen (piece) to the nearest gram.
2	Mount the specimen between the hammers (e.g., use modelling clay on the pedestal below) such that its smallest dimension is between the hammer faces.
3	Measure the specimen thickness at the point between the hammer faces if they are touching the specimen to the nearest 2.5–3 mm.
4	Implement suitable safety measures.
5	Initially raise the hammers as deemed suitable (e.g., 10 degrees from the vertical or more if the known material characteristics warrant).
6	Release the hammers to impact simultaneously on either side of the specimen.
7	Check the specimen for cracking or breaking. It is considered fractured if 33% or more of the original weight is broken off.
8	If the specimen is still whole, remeasure the thickness and increase the hammer angle by a suitable increment (e.g., 5 degrees from the vertical or more if the known material characteristics warrant) and return to the same orientation. Machines may also be marked off in impact energy units.
9	Repeat steps 4–8 until the specimen is broken. Record the last release angle used. If the particle continually chips away but does not break cleanly, note the same and disregard in calculations.
10	Note the number of major fragments from the broken specimen. This number and the particle weight do not enter the Wi calculations.
11	Repeat the above steps for all specimens.
12	Determine the specific gravity of the specimens.
13	For each specimen, tabulate the weight (in g), thickness (in mm), hammer release angle (in degrees), and number of major fragments.

5.1.4 Calculations

1	Calculate the impact energy used to break each specimen (equation 6):	$$C = \frac{110.2 \times (1 - \cos \alpha)}{d} \quad (6)$$ Where C is the impact energy (J/mm thickness), α is the impact angle (degrees from the vertical), and d is the specimen thickness (mm).
2	Calculate the mean impact energy for all specimens (C_{mean}).	
3	Calculate the Crushing Work Index (equation 7):	$$Wi_c = 48.5 \times 1.1023 \times \frac{C_{mean}}{sg} \quad (7)$$ Where Wi_c is the Crushing Work Index (kWh/t), C_{mean} is the mean impact energy for all specimens (J/mm thickness), and sg is the specific gravity of the specimens (unitless).

See Annex A for an example test report and calculations. Other test statistics may be calculated and reported.

5.2 Bond Rod Mill Wi Test

5.2.1 Apparatus

The Bond rod mill is made of metal, 305 mm maximum inside diameter, with a wave-type lining. The wave liners are 12.7 mm high, and there are eight of them with eight wave lifters each, 13 mm in height. The internal mill length is 610 mm. The grinding charge consists of six 31.8 mm and two 44.5 mm diameter steel rods, all 533.4 mm in length and weighing a total of 33,380 g.

The Bond rod mill runs at 46 rpm and has a revolution counter. In order to deal with material segregation at the ends, it is run in a level position for eight revolutions, tilted 5 degrees up for one revolution, and then tilted 5 degrees down for one revolution repeatedly during each grinding period.

Below the test feed control size of 12.7 mm, the normal root of 2 series sieve analysis equipment is used for test feed, test product, and circulating load (screen oversize) material dry size analyses. Dry screening on one or more sieves is done between grinding cycles, with the size of aperture ("closing screen aperture") chosen to close-circuit the test. Dry screening is suitable for rod mill test requirements, except final product size analysis, which may require wet and dry sieving.

5.2.2 Sample

Confirm the material is dry. It is best to start with approximately 14 kg of material with a specific gravity of 2.7, and proportionally more for material with higher specific gravity. This will allow for up to 10 grinding cycles. The material used for the feed size analysis can be reused for the grind test.

5.2.3 Procedure

Tests can be made at closing screen apertures from 4 mesh (4.76 mm) to 65 mesh (212 µm) but normally 8 mesh (2.38 mm) to 28 mesh (600 µm). The test control size chosen for these efficiency calculations is generally 14 mesh (1,190 µm).

At the end of each grinding period, the mill is discharged, and the ground material is screened at the designated closing screen aperture. The undersize is weighed, and an equal amount of fresh feed is added to the oversize to make up the total weight of the 1,250 cm^3 originally charged to the mill. This is returned to the mill and ground for the number of revolutions calculated to give a circulating load of 100%. The grinding cycles are continued until the grams of undersize produced per revolution reach equilibrium and/or reverse direction (change from increase to decrease or vice versa). Then the final circulating load and the undersize from the last three cycles combined are screen analyzed.

Steps:

1	Stage crush the rod mill test feed and screen through a 12.7 mm screen. Avoid overcrushing by screening, then crushing the oversize successively, until it all passes the 12.7 mm screen.
2	Rotary split the sample into suitably small batches, slightly smaller than the Ideal Potential Product (IPP). Further rotary split one or two of these batches into smaller sub-batches.
3	Conduct a screen analysis of the crushed test feed through the test closing screen aperture.
4	Determine the packed bulk density of the test material using a suitably sized container.
5	Determine the weight of 1,250 cm^3 of the material when packed. This is the material charge weight to be present in the rod mill.
6	Calculate the IPP for 100% circulating load, which is the material charge weight (in g) divided by two.
7	Make up the initial 1,250 cm^3 mill material charge from its calculated weight using the batches and sub-batches.
8	Place the material and rod charge in the mill and run for 50 revolutions, for example. This number can vary according to the closing screen aperture and experience of the laboratory. If the test feed contains 50% or more minus the closing screen aperture, assign zero as the first number of revolutions, screen the material at the closing screen, and make up the material to be ground to the desired weight with fresh feed.

9	Dump the material charge, screen it with the closing screen(s), and weigh screen oversize and undersize product.	
10	Determine the weight of net product in grams (equation 8):	Net product = Undersize product – Undersize in mill feed (8)
11	Determine the net product per revolution (net gpr) in grams (equation 9):	$\text{Net gpr} = \frac{\text{Net product}}{\text{No. revolutions}}$ (9)
12	Add new feed to oversize (circulating load) to bring it up to the desired material load in the mill.	
13	Calculate the number of mill revolutions to use for the next cycle (equation 10):	$\text{No. revolutions} = \frac{\text{(IPP – Weight of undersize in newly added fresh feed)}}{\text{Previous net gpr}}$ (10) Where IPP is the Ideal Potential Product for 100% circulating load (g), and net gpr is net product per revolution (g).
14	Repeat steps 8–13 for at least five grind cycles or until the net gpr reaches equilibrium and/or reverses its direction of increase or decrease.	
15	Determine the circulating load ratio for the last three cycles (equation 11):	$\text{Circulating load ratio} = \frac{\text{(Material charge – Mean product weight)}}{\text{Mean product weight}}$ (11)
16	Conduct screen analyses of the combined undersize (product) of the last three cycles and the oversize (circulating load) from the last cycle.	
17	The mean grams per revolution of the last three grind cycles is the rod mill gpr.	

5.2.4 Calculations

Bond Rod Mill Wi (equation 12):

$$Wi_{RM} = \frac{1.1023 \times 62}{P100^{0.23} \times gpr^{0.625} \times \left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \quad (12)$$

Where:

- Wi_{RM} is the Bond Rod Mill Work Index (kWh/t)
- P100 is the closing screen aperture size, ergo, the 100% pass size (μm)
- gpr is the grams (new minus closing screen aperture) per mill revolution
- P80 is the 80% passing size of the test product (μm)
- F80 is the 80% passing size of test feed (μm)
- 1.1023 is the conversion between metric tonnes and short tons
- 62 is an empirically fitted coefficient linking industrial rod mills to laboratory rod mills
- 0.23 and 0.625 are empirically fitted exponents linking industrial rod mills to laboratory rod mills
- 10 is the square root of 100 μm, which is reference size Bond chose to work with

See Annex B for an example test report and calculations. Other test statistics may be calculated and reported.

5.3 Bond Ball Mill Wi Test

5.3.1 Apparatus

The metal Bond ball mill is 30.5 cm inside diameter and 30.5 cm inside length, with rounded corners. It is smooth except for the door hole used for charging.

The grinding charge consists of 285 iron or steel balls (43 @ 36.8 mm diameter, 67 @ 29.7 mm diameter, 10 @ 25.4 mm diameter, 71 @ 19.1 mm diameter, and 94 @ 15.5 mm diameter) weighing a total of 20,125 g. The ball charge surface area is 5,432 cm^2. The mill runs at 70 rpm and has a revolution counter.

The normal root of 2 series sieve analysis equipment is used for test feed, test product, and circulating load (screen oversize) material size analyses. Dry screening on one or more sieves is done between grinding cycles when the closing screen aperture chosen to close-circuit the test is 75 µm (200 mesh) or coarser. Wet screening between grind cycles is used when the closing screen is 53 µm (270 mesh) or finer.

5.3.2 Sample

Confirm the material is dry. It is best to start with approximately 8 kg of material with a specific gravity of 2.7, and proportionally more with higher material specific gravity. This will allow for up to 10 grinding cycles. The material used for the feed size analysis can be re-used for the grind test.

5.3.3 Procedure

Tests can be made at a closing screen aperture of 28 mesh (600 µm) or finer. The test control size to be chosen for the test is described in Section 4.1.

At the end of each grinding period, the mill is discharged, and the discharge is screened at the designated closing screen aperture. The undersize is weighed, and an equal amount of fresh feed is added to the oversize to make up the total weight of the 700 cm^3 originally charged to the mill. This is returned to the mill and ground for the number of revolutions calculated to give a circulating load of 250%. The grinding cycles are continued until the grams of undersize produced per revolution reach equilibrium and/or reverse direction of increase or decrease. Then the final circulating load and the undersize from the last three cycles combined are screen analyzed.

Steps:

1	Stage crush the ball mill test feed sample and screen through a 3.36 mm (6 Tyler mesh) screen. Avoid overcrushing by screening, then crushing the oversize successively until it all passes the 3.36 mm screen.
2	Rotary split the sample into suitably small batches, slightly smaller than the IPP. Further rotary split one or two of these batches into smaller sub-batches.
3	Conduct a screen analysis of the crushed test feed, at least through the test closing screen aperture.
4	Determine the packed bulk density of the test material using a suitably sized container.
5	Determine the weight of 700 cm^3 of the material when packed. This is the material charge weight to be present in the ball mill. Note: variability in material charge weight due to method of packing is a source of experimental error. This may be addressed separately in the future.
6	Calculate the IPP for 250% circulating load, which is the material charge weight divided by 3.5.
7	Make up the initial 700 cm^3 mill material charge from its calculated weight using the batches and sub-batches.
8	Place the material and ball charge in the mill and run for 150 revolutions, for example. This number can vary according to the closing screen aperture and experience of the laboratory. If the fresh feed contains 30% or more minus the closing screen aperture, assign zero as the first number of revolutions, screen out the undersize, and add fresh feed to make up the charge to the desired weight to be ground first.
9	Dump the material charge, screen it with the closing screen(s), and weigh screen oversize and undersize product.
10	Determine the weight of net product in grams (equation 8).
11	Determine the net gpr (equation 9).
12	Add new feed to oversize (circulating load) to bring it up to the desired material load in the mill.

13	Calculate the number of mill revolutions to use for the next cycle (equation 10). Conduct the next grinding cycle.
14	Repeat steps 8–13 for at least five grind cycles, or until the net gpr reaches equilibrium, and/or reverses its direction of increase or decrease.
15	Determine the circulating load ratio for the last three cycles (equation 11).
16	Conduct screen analyses of the combined undersize (product) of the last three cycles and the oversize (circulating load) from the last cycle.
17	The mean grams per revolution of the last three grind cycles is the ball mill gpr.

5.3.4 Calculations

Bond Ball Mill Wi (equation 13):

$$Wi_{BM} = \frac{1.1023 \times 44.5}{P100^{0.23} \times gpr^{0.82} \times \left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \quad (13)$$

- Wi_{BM} is the Bond Ball Mill Work Index (kWh/t)
- P100 is the closing screen aperture size, ergo, the 100% pass size (µm)
- gpr is the net product per revolution (g)
- P80 is the 80% passing size of the test product (µm)
- F80 is the 80% passing size of test feed (µm)
- 1.1023 is the conversion between metric tonnes and short tons
- 44.5 is an empirically fitted coefficient linking industrial ball mills to laboratory ball mills
- 0.23 and 0.82 are empirically fitted exponents linking industrial ball mills to laboratory ball mills
- 10 is the square root of 100 µm, which is reference size Bond chose to work with

See Annex C for an example test report and calculations. Other test statistics may be calculated and reported.

5.4 Accuracy of Comparative Circuit Work Index Efficiency Determinations

The following sub-topics may be considered in future related GMG projects:

- Accuracy/sources of error in determining plant circuit W_{ioACT}
- Reproducibility of laboratory tests (in the same laboratory)
- Comparing efficiencies measured on the same circuit and parallel circuits
- Comparing efficiencies of different circuits
- Development and use of reference/calibration sample(s) and laboratories

6. RESOURCES, REFERENCES, AND RECOMMENDED READING

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ANNEX A

ANNEX A: Example test report for Bond Impact Crushing Wi test

Specimen		Thickness		Weight	Product pieces	Angle at breakage (degrees)	FT*LB per inch	Work index (kWh/t)	
No.	Rank	(inch)	(mm)	(g)				(short tons)	(metric tonnes)
1	6	2.20	56	692	2	60	18.6	15.7	17.1
2	22	2.36	60	926	7	130	57.0	48.3	52.7
3	7	2.56	65	1,074	2	75	23.7	20.1	21.9
4	9	2.44	62	824	5	75	24.9	21.1	23.0
5	5	2.28	58	576	3	60	18.0	15.2	16.6
6	8	2.24	57	1,046	2	70	24.0	20.4	22.2
7	4	1.97	50	786	2	55	17.8	15.0	16.4
8	11	1.85	47	600	3	65	25.6	21.7	23.7
9	2	1.89	48	676	6	45	12.7	10.8	11.8
10	12	2.36	60	766	3	75	25.7	21.8	23.8
11	1	2.17	55	754	2	45	11.1	9.4	10.3
12	19	2.56	65	1,247	2	120	48.1	40.7	44.4
13	10	2.13	54	472	4	70	25.4	21.5	23.5
14	23	1.97	50	1,050	2	115	59.3	50.2	54.8
15	24	1.97	50	666	4	130	68.4	57.9	63.2
16	21	2.28	58	1,150	4	125	56.5	47.8	52.2
17	18	2.36	60	1,160	2	110	46.6	39.4	43.0
18	16	2.48	63	706	2	100	38.8	32.8	35.8
19	17	2.17	55	1,010	3	100	44.4	37.6	41.0
20	20	2.17	55	1,222	4	110	50.8	43.0	46.9
21	13	1.89	48	426	3	70	28.6	24.2	26.4
22	15	2.17	55	510	2	90	37.9	32.1	35.0
23	3	2.48	63	658	2	55	14.1	11.9	13.0
24	14	2.20	56	1,156	3	85	34.0	28.7	31.3
Average		2.21	56.3	839.7	3.08		33.8	28.6	31.3

Notes: This output is transcribed from an actual test report, therefore some units are not SI compliant.
Sample density = 3.06 kg/L

ANNEX B

ANNEX B: Example test report for Bond rod mill Wi test

Period	Revolutions of mill	Grams of product	Grams in feed	Net grams produced	Net grams per revolution (gpr)
1	200.0	1,315.1	238.0	1,077.1	5.386
2	197.0	1,411.3	131.3	1,280.0	6.497
3	162.0	1,308.2	140.9	1,167.3	7.205
4	147.0	1,394.2	130.5	1,263.7	8.596
5	122.0	1,226.9	139.1	1,087.8	8.916
6	120.0	1,180.2	122.4	1,057.8	8.815

Lab mill feed is 1.91 kg/L, packed (= 119.0 lb/ft^3). Equivalent to 2384 g (1,250 cm^3) in mill
Ideal Potential Product = 1,191 g
Specific gravity = 3.06
Average of last 2 periods, 98.1% circulating load
Grindability at 1,180 µm = 8.865 net Gpr

Size of sieve		Test feed percentage		Circulating load percentage		Test product percentage	
Tyler Mesh	ASTM µm	On	Passing	On	Passing	On	Passing
1/2	13,200	0.00	100.00	0.00	100.00	0.00	100.00
3/8	9,500	28.90	71.10	0.88	99.12	0.00	100.00
3	6,700	29.30	41.80	4.89	94.23	0.00	100.00
4	4,750	14.89	26.90	5.84	88.39	0.00	100.00
6	3,350	6.19	20.71	8.99	79.39	0.00	100.00
8	2,360	5.21	15.50	15.49	63.90	0.00	100.00
10	1,700	4.05	11.45	26.98	36.92	0.00	100.00
14	1,180	1.47	9.98	35.22	1.70	0.52	99.48
20	850	2.37	7.61	1.67	0.03	23.61	75.87
28	600	1.47	6.14	0.00	0.00	15.52	60.35
35	425	1.16	4.98	0.00	0.00	11.90	48.45
48	300	0.86	4.12	0.00	0.00	8.41	40.04
65	212	0.61	3.51	0.00	0.00	6.02	34.02
100	150	0.56	2.96	0.00	0.00	4.72	29.30
150	106	0.47	2.49	0.00	0.00	3.82	25.49
200	75	0.47	2.02	0.00	0.00	3.95	21.54
270	53	0.00	0.00	0.00	0.00	0.00	0.00
325	45	0.00	0.00	0.00	0.00	0.00	0.00
400	38	0.00	0.00	0.00	0.00	0.00	0.00
500	26	0.00	0.00	0.00	0.00	0.00	0.00
PAN	0	2.02	0.00	0.03	0.00	21.54	0.00

Screen analyses do not represent plant operation results
80% passing feed size = 10,645 µm
80% passing product size = 906 µm
Bond Work Index from above test = 14.6 kWh/t (metric basis) or 13.2 kWh/t (short tons basis)

Note: This output is transcribed from an actual test report, therefore, some units are not SI compliant.

ANNEX C

ANNEX C: Example test report for Bond ball mill Wi test

Period	Revolutions of mill	Grams of product	Grams in feed	Net grams produced	Net grams per revolution (gpr)
1	225.0	444.7	96.6	348.1	1.547
2	229.0	408.2	31.8	376.4	1.644
3	217.0	409.1	29.2	379.9	1.751
4	204.0	397.9	29.3	368.6	1.807
5	198.0	393.0	28.4	364.6	1.841
6	194.0	382.5	28.1	354.4	1.827

Lab mill feed is 1.93 kg/L, packed (= 120.4 lb/ft^3). Equivalent to 1,351 g (700 cm^3) in mill
Ideal Potential Product = 385.6 g
Specific gravity = 3.06
Average of last 3 periods, 245.4% circulating load
Grindability at 106 µm = 1.825 net gpr

Size of sieve		Test feed percentage		Circulating load percentage		Test product percentage	
Tyler Mesh	ASTM µm	On	Passing	On	Passing	On	Passing
1/2	13,200	0.00	100.00	0.00	100.00	0.00	100.00
1/2	13,200	0.00	100.00	0.00	100.00	0.00	100.00
3/8	9,500	0.00	100.00	0.00	100.00	0.00	100.00
3	6,700	0.00	100.00	0.00	100.00	0.00	100.00
4	4,750	0.00	100.00	0.00	100.00	0.00	100.00
6	3,350	0.00	100.00	0.00	100.00	0.00	100.00
8	2,360	32.51	67.49	9.91	90.09	0.00	100.00
10	1,700	21.09	46.40	15.79	74.30	0.00	100.00
14	1,180	6.41	39.99	7.81	66.50	0.00	100.00
20	850	13.88	26.11	6.44	60.06	0.00	100.00
28	600	6.46	19.65	5.32	54.74	0.00	100.00
35	425	3.95	15.70	6.39	48.35	0.00	100.00
48	300	2.99	12.71	8.02	40.33	0.00	100.00
65	212	2.40	10.30	12.27	28.06	0.00	100.00
100	150	1.76	8.54	11.75	16.30	0.00	100.00
150	106	1.39	7.15	15.66	0.64	3.04	96.96
200	75	1.55	5.61	0.64	0.00	20.17	76.80
270	53	1.23	4.38	0.00	0.00	14.64	62.15
325	45	0.59	3.79	0.00	0.00	3.59	58.56
400	38	0.32	3.47	0.00	0.00	9.81	48.76
500	26	0.00	0.00	0.00	0.00	9.81	38.95

Screen analyses do not represent plant operation results
80% passing feed size = 2,946 µm
80% passing product size = 80 µm
Bond Work Index from above test = 11.0 kWh/t (metric basis) or 10.0 kWh/t (short tons basis)

Note: This output is transcribed from an actual test report, therefore some units are not SI compliant.