

GLOBAL MINING GUIDELINES GROUP



20150505_Bond_Efficiency-GMG-ICE-v1-r04

Determining the Bond Efficiency of industrial grinding circuits

SUBMITTED BY

The Bond Efficiency Guideline Sub-Committee

VERSION DATE

05 May 2015

Annexes: 26 Mar 2015

APPROVED BY

Vote of the Industrial Comminution Efficiency Working Group

05 May 2015

and

GMG Governing Council

11 May 2015

EDITED BY

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20 Aug 2015

PUBLISHED

18 Feb 2016

DATE DOCUMENT TO BE REVIEWED

05 May 2020

**PREPARED BY THE BOND WORK INDEX SUB-COMMITTEE
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1. FOREWORD

The Global Mining Guidelines Group (GMG) is a global, multi-stakeholder community to advance the availability and use of standards and guidelines for the international mining industry. This GMG document was prepared by a GMG working group. Draft documents are checked and approved by working group members, prior to approval by the GMG Governing Council.

Formed as part of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM), GMG is supported by CIM and three other Partner Organizations: the Australasian Institute of Mining and Metallurgy (AusIMM), the Southern African Institute of Mining and Metals (SAIMM), and the Surface Mining Association for Research and Technology (SMART), as well as its Member Companies and participants.

Please note: if some of the elements of this document are subject to patent rights, the GMG and CIM are not responsible for identifying such patent rights.

2. DEFINITIONS OF TERMS, SYMBOLS, AND 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	Equipment power (kW)
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)
W	Specific energy (work) input (kWh/t)
Wi	Bond Work Index (kWh/t)
$W_{i_{\text{BM}}}$	Bond Ball Mill Test Work Index (kWh/t)
$W_{i_{\text{C}}}$	Bond Impact Crushing Test Work Index (kWh/t)
$W_{i_{\text{oACT}}}$	Actual Operating Bond Work Index determined from measurements on the circuit (kWh/t)
$W_{i_{\text{RM}}}$	Bond Rod Mill Test Work Index (kWh/t)
$W_{i_{\text{STD}}}$	Standard Circuit Bond Work Index (expected or designed) used for circuit design. Specific energy requirement at the drive pinions.

3. KEYWORDS

Work Index, Work Index Efficiency, Bond Work Index testing

4. INTRODUCTION AND BACKGROUND

The Bond method allows for quantification and comparison of relative energy efficiencies of most industrial comminution circuits. It is an essential tool for managing the important business (cost) of grinding.

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

5. SCOPE

This Bond Efficiency determination applies to most brittle materials in their naturally occurring (unscalped) size distributions being treated in size reduction circuits down to an 80% passing size of the circuit product (P80) of approximately 70 μm . Unusually shaped materials (e.g., mica) should be regarded with caution. The Bond Work Index (Wi) is the specific energy associated with a standard amount of size reduction: from a very large F80 (80% passing circuit feed) of approximately infinity to a P80 of 100 μm .

6. OTHER USEFUL DOCUMENTS

The sampling and surveying guideline (GMG, under approval) will provide guidance on how to collect information related to the operation of the circuit (F80, P80, power and mill feed rate).

7. DETERMINING THE BOND EFFICIENCY OF A GRINDING CIRCUIT

7.1 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 8).. 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.

Calculations:

1. Calculate the Actual Operating Bond Work Index of the grinding circuit.
 - Estimate the F80 and P80.
 - Calculate the work or specific energy input from the size reduction equipment power and circuit tonnage (equation 1). Auxiliary equipment power is excluded.

$$W = \frac{P}{T} \tag{1}$$

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):

$$W_{i_{oACT}} = \frac{W}{\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \tag{2}$$

Where, $W_{i_{oACT}}$ 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 ($W_{i_{STD}}$) for the material being processed (equation 3).

$$W_{i_{STD}} = \frac{W_{total}}{\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right)} \tag{3}$$

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 $W_{i_{STD}}$ (Figure 1). It is also the “design” W_i for this circuit based on the laboratory W_i 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). This Bond Efficiency determination should not be applied to circuits with a P80 finer than approximately 70 μm without making qualifications.

3. Calculate the circuit W_i Efficiency Ratio (equation 4):

$$W_i \text{ Efficiency Ratio} = \frac{W_{i_{STD}}}{W_{i_{oACT}}} \tag{4}$$

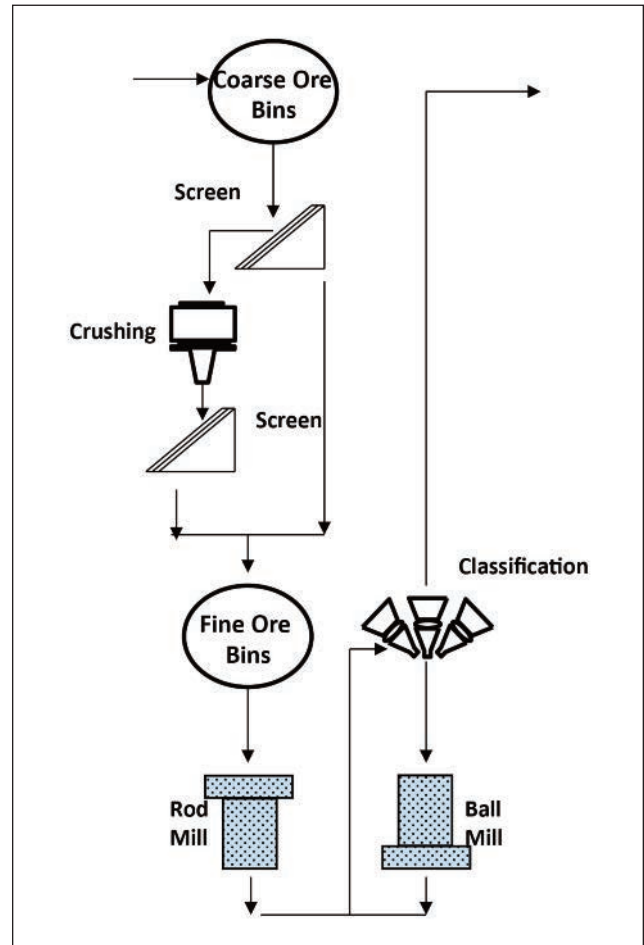


Figure 1. The Bond Standard Circuit

Where, $W_{i_{STD}}$ is the Standard Circuit Bond Work Index (kWh/t) and $W_{i_{oACT}}$ is the Actual Operating Bond Work Index (kWh/t).

- If the W_i Efficiency Ratio is 1.0 or 100%, the circuit is performing with the same efficiency as the Bond Standard Circuit (and the ore $W_i =$ circuit operating W_i), 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 W_i 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 W_i 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 W_i Efficiency Ratio; it can be used by multiplying against the laboratory-derived W_{iSTD} to give the actual operating work index of a circuit, W_{iOACT} .

$$\text{Bond Standard Circuit Energy Factor} = \frac{W_{iOACT}}{W_{iSTD}} \quad (5)$$

7.2 Demonstration/Example Calculations

7.2.1 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 W_i of circuit feed ore (kWh/t)	16.1
Test rod mill W_i of circuit feed ore (kWh/t)	16.1

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

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

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

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

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.

7.2.2 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 W_i of crushing (kWh/t)	9.8
Test W_i of rod mill (kWh/t)	9.5
Test W_i 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)

$$W_{iOACT} = \frac{8.56}{\left(\frac{10}{\sqrt{155}} - \frac{10}{\sqrt{16,000}}\right)} = 11.8 \text{ kWh/t}$$

- Bond Standard Circuit:

Assume the test W_i of the rod mill (9.5) applies from the actual rod mill feed size of 19,300 μm (although some of this work might ideally be done by crushers to achieve a rod mill F80 of 16,000 μm) to a rod mill (circuit) product size of 1,000 μm .

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

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

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

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

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

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

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 W_i crushing (kWh/t)	16.0
Test W_i of rod mill (kWh/t)	14.5
Test W_i of ball mill (kWh/t)	13.8

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

- Bond Standard Circuit:

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

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

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

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

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

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

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

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.

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

8. 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 Sub-Committee of the Industrial Comminution Efficiency Working Group of the GMG. 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 reflect 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 W_i 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 W_i values among laboratories.

Discussion of test result variability (due to the nature of the ore, nature of specimens tested, and test equipment and procedures) will come later.

8.1 Bond Crushing W_i Test for Bond Efficiency Determinations

The Bond impact crushing work index test provides the coarse size work index for the $W_{i\text{STD}}$ 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.

8.1.1 Apparatus

The Bond impact crushing work index test provides the coarse size work index for the $W_{i\text{STD}}$ 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.

Two hammers weighing 13.6 kg each are pendulum-mounted, such that when released, they track back on the same line they were raised and impact simultaneously on opposite sides of each rock specimen. The hammer faces are 51 mm \times 51 mm \times 25.4 mm. 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 8.1.4).

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.

8.1.2 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 par-

allel faces that are between 51 and 76 mm in thickness. If this is the case, the Impact Crushing W_i nevertheless can be used in Bond Efficiency calculations. A minimum of ten (preferably twenty) pieces are tested.

8.1.3 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 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 W_i 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.

8.1.4 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):

$$W_{i_c} = 48.5 \times 1.1023 \times \frac{C_{\text{mean}}}{\text{sg}} \quad (7)$$

Where, W_{i_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 example test report and calculations. Other test statistics may be calculated and reported.

8.2 Bond Rod Mill W_i Test

8.2.1 Apparatus

The Bond rod mill is made of metal, 305 mm maximum inside diameter, with a wave-type lining. 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.

8.2.2 Sample

Ensure 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 re-used for the grind test.

8.2.3 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 (300 μm). The test control size chosen for these efficiency calculations is generally 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 cm³ 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 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. Conduct a screen analysis of the crushed test feed through the test closing screen aperture.
3. Determine the packed bulk density of the test material using a suitably sized container.
4. Determine the weight of 1,250 cm³ of the material when packed. This is the material charge weight to be present in the rod mill.
5. Calculate the Ideal Potential Product (IPP) for 100% circulating load, which is the material charge weight (in g) divided by two.
6. 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.
7. Make up the initial 1,250 cm³ 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 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):

$$\text{Net product} = \frac{\text{Undersize product} - \text{Undersize in mill feed}}{\text{No. revolutions}} \quad (8)$$

11. Determine the net product per revolution (net Gpr) in grams (equation 9):

$$\text{Net Gpr} = \frac{\text{Net product}}{\text{No. revolutions}} \quad (9)$$

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):

$$\text{No. revolutions} = \frac{\text{IPP} - \text{Weight of undersize in newly added fresh feed}}{\text{Previous net Gpr}} \quad (10)$$

Where IPP is the Ideal Potential Product for 100% circulating load (g), and net Gpr is net product per revolution (g).

14. Repeat steps 9–13 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):

$$\text{Circulating load ratio} = \frac{\text{Material charge} - \text{Mean product weight}}{\text{Mean product weight}} \quad (11)$$

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.

8.2.4 Calculations

Bond Rod Mill W_i (equation 12):

$$W_{i_{RM}} = \frac{1.1023 \times 62}{P_{100}^{0.23} \times Gpr^{0.625} \times \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \quad (12)$$

Where, $W_{i_{RM}}$ is the Bond Rod Mill W_i (kWh/t), P_{100} is the closing screen aperture (μm), Gpr is the net product per revolution (g), P_{80} is the 80% passing size of circuit product (μm), and F_{80} is the 80% passing size of circuit feed (μm).

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

8.3 Bond Ball Mill Wi Test

8.3.1 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 cm². 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.

8.3.2 Sample

Ensure 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.

8.3.3 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 7.1.

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 cm³ 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 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 over-crushing by screening, then crushing the oversize successively, until it all passes the 3.36 mm screen.
2. Conduct a screen analysis of the crushed test feed, at least through the test closing screen aperture.
3. Determine the packed bulk density of the test material using a suitably sized container.

4. Determine the weight of 700 cm³ of the material when packed. This is the material charge weight to be present in the ball mill.
5. Calculate the IPP for 250% circulating load, which is the material charge weight divided by 3.5.
6. 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.
7. Make up the initial 700 cm³ 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 under-size, 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):
14. Repeat steps 9–13 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.

8.3.4 Calculations

Bond Ball Mill Wi (equation 13):

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

Where, $W_{i_{BM}}$ is the Bond Ball Mill Wi (kWh/t), P100 is closing screen aperture (µm), Gpr is the net grams per revolution of product, P80 is the 80% passing size of product (µm), and F80 is the 80% passing size of circuit feed.

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

8.4 Accuracy of Comparative Circuit Work Index Efficiency Determinations

This will follow in an addendum to this guideline. Subtopics will include the following:

- accuracy/sources of error in determining plant circuit $W_{i_{oACT}}$;
- reproducibility of laboratory tests (in the same laboratory);
- comparing efficiencies measured on the same circuit and parallel circuits;

- comparing efficiencies of different circuits; and
- development and use of reference/calibration sample(s) and laboratories.

9. DATABASE OF BOND GRINDING CIRCUIT EFFICIENCIES

This database is being developed and will follow in an addendum to this guideline. See slide no. 13 in the presentation “Bond Efficiency SLC (rev3)-print.pdf” available for download at the GMG website for preliminary “Examples from DataBase”.

10. RESOURCES, REFERENCES, AND RECOMMENDED READING

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ANNEX A: EXAMPLE TEST REPORT FOR BOND IMPACT CRUSHING WI TEST

Specimen		Thickness		Weight (g)	Product pieces	Angle at breakage (degrees)	FT*LB per inch	Work index (kWh/t)	
No.	Rank	(inch)	(mm)					(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	1074	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	1046	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	1247	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	1050	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	1150	4	125	56.5	47.8	52.2
17	18	2.36	60	1160	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	1010	3	100	44.4	37.6	41.0
20	20	2.17	55	1222	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	1156	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: 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	1315.1	238.0	1077.1	5.386
2	197.0	1411.3	131.3	1280.0	6.497
3	162.0	1308.2	140.9	1167.3	7.205
4	147.0	1394.2	130.5	1263.7	8.596
5	122.0	1226.9	139.1	1087.8	8.916
6	120.0	1180.2	122.4	1057.8	8.815

Lab mill feed is 1.91 kg/L, packed (= 119.0 lb/ft³). Equivalent to 2384 g (1250 cm³) in mill
 Ideal Potential Product = 1191 g
 Specific gravity = 3.06
 Average of last 2 periods, 98.1% circulating load
 Grindability at 1180 µm = 8.865 net Gpr

Size of sieve		Lab mill feed percentage		Circulating load percentage		Last per product percentage	
Tyler Mesh	ASTM µm	On	Passing	On	Passing	On	Passing
1/2	13200	0.00	100.00	0.00	100.00	0.00	100.00
3/8	9500	28.90	71.10	0.88	99.12	0.00	100.00
3	6700	29.30	41.80	4.89	94.23	0.00	100.00
4	4750	14.89	26.90	5.84	88.39	0.00	100.00
6	3350	6.19	20.71	8.99	79.39	0.00	100.00
8	2360	5.21	15.50	15.49	63.90	0.00	100.00
10	1700	4.05	11.45	26.98	36.92	0.00	100.00
14	1180	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	*00.00	15.52	60.35
35	425	1.16	4.98	0.00	*00.00	11.90	48.45
48	300	0.86	4.12	0.00	*00.00	8.41	40.04
65	212	0.61	3.51	0.00	*00.00	6.02	34.02
100	150	0.56	2.96	0.00	*00.00	4.72	29.30
150	106	0.47	2.49	0.00	*00.00	3.82	25.49
200	75	0.47	2.02	0.00	*00.00	3.95	21.54
270	53	0.00	*00.00	0.00	*00.00	0.00	*00.00
325	45	0.00	*00.00	0.00	*00.00	0.00	*00.00
400	38	0.00	*00.00	0.00	*00.00	0.00	*00.00
500	26	0.00	*00.00	0.00	*00.00	0.00	*00.00
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 = 10645 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: 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/ft³). Equivalent to 1351 g (700 cm³) 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		Lab mill feed percentage		Circulating load percentage		Last per product percentage	
Tyler Mesh	ASTM µm	On	Passing	On	Passing	On	Passing
1/2	13200	0.00	100.00	0.00	100.00	0.00	100.00
3/8	9500	0.00	100.00	0.00	100.00	0.00	100.00
3	6700	0.00	100.00	0.00	100.00	0.00	100.00
4	4750	0.00	100.00	0.00	100.00	0.00	100.00
6	3350	0.00	100.00	0.00	100.00	0.00	100.00
8	2360	32.51	67.49	9.91	90.09	0.00	100.00
10	1700	21.09	46.40	15.79	74.30	0.00	100.00
14	1180	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	*00.00	14.64	62.15
325	45	0.59	3.79	0.00	*00.00	3.59	58.56
400	38	0.32	3.47	0.00	*00.00	9.81	48.76
500	26	0.00	*00.00	0.00	*00.00	9.81	38.95
PAN	0	3.47	0.00	0.00	*00.00	38.95	0.00

Screen analyses do not represent plant operation results
 80% passing feed size = 2946 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.