Determining the Bond Efficiency of industrial grinding circuits

SUBMITTED BY
The Bond Efficiency Guideline 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)
- Cmean: 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)
- GP: 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)
- WiBM: Bond Ball Mill Test Work Index (kWh/t)
- WiC: Bond Impact Crushing Test Work Index (kWh/t)
- WiD: Actual Operating Bond Work Index determined from measurements on the circuit (kWh/t)
- WiRM: Bond Rod Mill Test Work Index (kWh/t)
- WiSTD: 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.
2. Conduct Wi test(s) on the circuit feed (see Section 8).
3. 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.

\[ W = \frac{P}{T} \]  

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):

\[ W_{\text{ACT}} = \frac{W}{\sqrt{P_{80}}} \cdot \frac{10}{\sqrt{F_{80}}} \]  

Where, \( W_{\text{ACT}} \) is the Actual Operating Bond Work Index (kWh/t), \( W \) is the specific energy input (kWh/t), \( P_{80} \) is the 80% passing size of product (µm), and \( F_{80} \) is the 80% passing size of circuit feed (µm).

2. Calculate the Standard Circuit Bond Work Index (\( W_{\text{STD}} \)) for the material being processed (equation 3).

\[ W_{\text{STD}} = \frac{W_{\text{total}}}{\sqrt{P_{80}}} \cdot \frac{10}{\sqrt{F_{80}}} \]  

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 \( W_{\text{STD}} \) (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). 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 Wi Efficiency Ratio (equation 4):

\[ \text{Wi Efficiency Ratio} = \frac{W_{\text{STD}}}{W_{\text{ACT}}} \]  

Where, \( W_{\text{STD}} \) is the Standard Circuit Bond Work Index (kWh/t) and \( W_{\text{ACT}} \) 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\textsubscript{STD} to give the actual operating work index of a circuit, Wi\textsubscript{oACT}.

\[
\text{Bond Standard Circuit Energy Factor} = \frac{\text{Wi}_{\text{oACT}}}{\text{Wi}_{\text{STD}}}
\]

7.2 Demonstration/Example Calculations

7.2.1 Generic Circuit Calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power draw of mill(s) at pinion(s) (kW)</td>
<td>3,150</td>
</tr>
<tr>
<td>Circuit dry tonnage (metric t/h)</td>
<td>450</td>
</tr>
<tr>
<td>Circuit P80 (µm)</td>
<td>212</td>
</tr>
<tr>
<td>Circuit F80 (µm)</td>
<td>2,500</td>
</tr>
<tr>
<td>Test ball mill Wi of circuit feed ore (kWh/t)</td>
<td>16.1</td>
</tr>
<tr>
<td>Test rod mill Wi of circuit feed ore (kWh/t)</td>
<td>16.1</td>
</tr>
</tbody>
</table>

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

\[
\text{Wi}_{\text{oACT}} = \frac{7}{\left(\frac{10}{\sqrt{16,000}} - \frac{10}{\sqrt{2,500}}\right)} = 14.4 \text{ kWh/t}
\]

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

Bond Standard Circuit Energy Factor = \frac{14.4}{16.1} = 0.89 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

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

\[
\text{Wi}_{\text{oACT}} = \frac{8.56}{\left(\frac{10}{\sqrt{155}} - \frac{10}{\sqrt{16,000}}\right)} = 11.8 \text{ kWh/t}
\]

- Bond Standard Circuit:
  Assume the test Wi 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.

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

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

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

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

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

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

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

\[
\text{Wi}_{\text{oACT}} = \frac{14.6}{\left(\frac{10}{\sqrt{125}} - \frac{10}{\sqrt{165,000}}\right)} = 16.8 \text{ kWh/t}
\]

- Bond Standard Circuit:

\[
W_1 = 16.0 \times \left(\frac{10}{\sqrt{16,000}} - \frac{10}{\sqrt{165,000}}\right) = 0.9 \text{ kWh/t}
\]
DETERMINING THE BOND EFFICIENCY OF INDUSTRIAL GRINDING CIRCUITS

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

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

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

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

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

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 \( W \) 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.

8.1 Bond Crushing Wi Test for Bond Efficiency Determinations

The Bond impact crushing work index test provides the coarse size work index for the \( W_{\text{STD}} \) 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 \( W_{\text{STD}} \) 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 × 51 mm × 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 “\( \alpha \)” 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 Wi 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 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.

8.1.4 Calculations
1. Calculate the impact energy used to break each specimen (equation 6):
   \[ C = \frac{110.2 \times (1 - \cos \alpha)}{d} \]  
   Where, \( C \) is the impact energy (J/mm thickness), \( \alpha \) is the impact angle (degrees from the vertical), and \( d \) is the specimen thickness (mm).
2. Calculate the mean impact energy for all specimens \( (C_{\text{mean}}) \).
3. Calculate the Crushing Work Index (equation 7):
   \[ W_{i,c} = 48.5 \times 1.1023 \times \frac{C_{\text{mean}}}{\text{sg}} \]  
   Where, \( W_{i,c} \) is the Crushing Work Index (kWh/t), \( C_{\text{mean}} \) is the mean impact energy for all specimens (J/mm thickness), and \( \text{sg} \) 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 Wi 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):
\[ \text{Net product} = \text{Undersize product} - \text{Undersize in mill feed} \] (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):
\[ \text{No. revolutions} = \frac{(\text{IPP} - \text{Weight of undersize in newly added fresh feed})}{\text{Previous net Gpr}} \] (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 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):
\[ \text{Circulating load ratio} = \frac{(\text{Material charge} - \text{Mean product weight})}{\text{Mean product weight}} \] (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 Wi (equation 12):
\[ \text{Wi}_{\text{RM}} = \frac{1.1023 \times 62}{P100^{0.23} \times \text{Gpr}^{0.625} \times \left( \frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}} \right)} \] (12)
Where, \( \text{Wi}_{\text{RM}} \) is the Bond Rod Mill Wi (kWh/t), P100 is the closing screen aperture (µm), Gpr is the net product per revolution (g), P80 is the 80% passing size of circuit product (µm), and F80 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 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):
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):

\[
W_{\text{BM}} = \frac{1.1023 \times 44.5}{P_{100}^{0.23} \times G_{\text{pr}}^{0.82} \times \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)}
\]

Where, \(W_{\text{BM}}\) is the Bond Ball Mill Wi (kWh/t), \(P_{100}\) is closing screen aperture (µm), \(G_{\text{pr}}\) is the net grams per revolution of product, \(P_{80}\) is the 80% passing size of product (µm), and \(F_{80}\) 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 \( W_{ioACT} \);
• 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
Rowland, C. A., Jr. (1976). The tools of power power: The Bond work index, a tool to measure grinding efficiency. AIME Fall Meeting, Denver, CO.
### ANNEX A: EXAMPLE TEST REPORT FOR BOND IMPACT CRUSHING WI TEST

<table>
<thead>
<tr>
<th>No.</th>
<th>Rank</th>
<th>Thickness (inch)</th>
<th>Weight (g)</th>
<th>Product pieces</th>
<th>Angle at breakage (degrees)</th>
<th>FT-LB per inch</th>
<th>Work index (kWh/t) (short tons) (metric tonnes)</th>
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</thead>
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<td>Average: 2.21</td>
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</table>

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

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<tr>
<th>Period</th>
<th>Revolutions of mill</th>
<th>Grams of product</th>
<th>Grams in feed</th>
<th>Net grams produced</th>
<th>Net grams per revolution (Gpr)</th>
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</thead>
<tbody>
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</tr>
</tbody>
</table>

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 3 periods, 98.1% circulating load

Grindability at 1180 µm = 8.865 net Gpr

<table>
<thead>
<tr>
<th>Size of sieve</th>
<th>Lab mill feed percentage</th>
<th>Circulating load percentage</th>
<th>Last per product percentage</th>
</tr>
</thead>
<tbody>
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<td>Tyler Mesh</td>
<td>µm</td>
<td>On</td>
<td>Passing</td>
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<td>100.00</td>
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<td>71.10</td>
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<td>6.14</td>
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</tr>
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<td>*0.00</td>
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<td>*0.00</td>
</tr>
<tr>
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<td>2.02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

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 = 146 kWh/t (metric basis) or 132 kWh/t (short tons basis)

Note: This output is transcribed from an actual test report, therefore some units are not SI compliant.
Grindability at 106 µm = 1.825 net Gpr
Average of last 3 periods, 245.4% circulating load
Specific gravity = 3.06
Bond Work Index from above test = 11.0 kWh/t (metric basis) or 10.0 kWh/t (short tons basis)
80% passing product size = 80 µm
Screen analyses do not represent plant operation results

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

<table>
<thead>
<tr>
<th>Period</th>
<th>Revolutions of mill</th>
<th>Grams of product</th>
<th>Grams in feed</th>
<th>Net grams produced</th>
<th>Net grams per revolution (Gpr)</th>
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</thead>
<tbody>
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</table>

Lab mill feed is 1.93 kg/L, packed (= 120.4 lb/ft³). Equivalent to 1351 g (700 cm³) in mill.

---

**ANNEX C: EXAMPLE TEST REPORT FOR BOND BALL MILL WI**

<table>
<thead>
<tr>
<th>Size of sieve</th>
<th>Lab mill feed percentage</th>
<th>Circulating load percentage</th>
<th>Last per product percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyler</td>
<td>ASTM</td>
<td>On</td>
<td>Passing</td>
</tr>
<tr>
<td>Mesh</td>
<td>µm</td>
<td>On</td>
<td>Passing</td>
</tr>
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<td>100.00</td>
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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.